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ARC-RELATED MESOZOIC BASINS OF NORTHERN MEXICO: THEIR ORIGIN, TECTONIC INVERSION AND INFLUENCE ON ORE LOCALIZATION

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by

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Dedication

This work is dedicated to Steven Clabaugh who opened my eyes to not only the broader world of geology but also to the concepts of plate tectonics that showed me that there was room for major new concepts in the science of geology. Steve encouraged creativity by producing an environment where we could agree to disagree and conforming to convention was not required. Finally Steve introduced me to volcanic rocks that formed the foundation for the first half of my career, opening many opportunities as I moved through life.

I would also like to dedicate this to my wife of 45 years Patricia who without her steadying influence I could not have achieved what I have. She is the keel to my sails with which I chase the wind.

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Kevin McAndrews, David Simpson and Richard Leveille of Minera Kennecott gave me wide latitude to carry out reconnaissance mapping in Mexico and specific project mapping during the 1990's, that provided the foundation of this study. Rich Kyle secured me a position in the Doctoral Program at the Jackson School of Geosciences of the University of Texas at Austin and has invested a major effort in getting the dissertation to a readable state. Following my achieving candidacy, Peter Megaw of IMDEX-Cascabel S.A. de C.V. and MAG Silver Corporation hired me as a consulting geologist with the understanding I could publish much of the mapping and logging results I produced as parts of my dissertation. MAG Silver funded my studies on most of the specific projects and funded most of the radiometric ages analyzed for this study. Additional funding also used for radiometric dating came from the Don R. Boyd Memorial Grant handled by the AAPG and matching funds from the Geology Foundation. The Geology Foundation funded my tuition during the first five years.

William Muehlberger was my first Co-Supervisor and having also taught me Geomorphology in 1969 was unfortunately not able to see the end results of my endeavor to further advance my knowledge and that of others. Timothy Lawton, my current Co-Supervisor and outside committee member, assisted greatly both directly in shaping the focus of this study and from his many publications on northern Mexico. I would also like to acknowledge the assistance of Mark Cloos, Brian Horton and Brent Elliott, my other committee members, for their patience and assistance. Courses from Mark Cloos, James Connolly, William Fisher, Ciff Frohlich, John Lassiter, Charles Kerans, Richard Kyle, and Randall Marrett and discussions with Stephen Grand greatly broadened my geologic perspective during these studies.

ARC-RELATED MESOZOIC BASINS OF NORTHERN MEXICO: THEIR ORIGIN, TECTONIC INVERSION AND INFLUENCE ON ORE LOCALIZATION

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The University of Texas at Austin, 2015

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New structural mapping and radiometric dating in northern Mexico integrated with previous studies indicate the need for revision of current regional tectonic models. The Mezcalera Marginal Basin, an autochthonous Jurassic-Lower Cretaceous basin exposed from southern Arizona to Guerrero replaces accreted terrane models. The lack of significant documentable offsets of this marginal basin provides evidence that contradict proposed major Mexican transform faults in northern Mexico. A left-lateral Cenomanian transpressional fault along which the Caborca and related terranes and offset Bisbee Group strata were displaced is documented by east-directed thrusting of the translated basement and supracrustal strata over the autochthonous Mezcalera Basin strata.

Oxfordian (149 Ma) submarine volcanic domes at Batopilas, Chihuahua indicate possible westward migration of the Nazas arc from central Mexico across the Mezcalera Marginal Basin, and 124 to 138 Ma dates on Bisbee Group Morita Formation tuffs infer Alisitos arc volcanism to the west. The well documented Late Cretaceous through Miocene arc migration can thus be projected to the Early Jurassic. Oceanic plate rollback toward the Pacific from the Jurassic through the Early Cretaceous presents the simplest

model for the proposed arc migration as well as coincident extension of the Mexican continent.

A previously unrecognized intracratonic basin, the Carrizal Basin, a probable northern extension of the Mexican Basin, is documented west of the Chihuahua Basin. The older usage Aldama Platform is divided into the Casas Grandes Platform to the west and the Florida-Aldama Ridge to the east of the Carrizal Basin.

Basin inversion as defined by mapping of bivergent out-of-the-basin thrusting along both sides of both the Carrizal and Mexican Intracratonic Basins suggests inversion as the principal tectonic process that produced the Sierra Madre Oriental fold belts. Stratigraphic relationships document the inception of tectonic shortening as Late Cenomanian and a folded 43.7 Ma rhyolite flow at Division de Norte, Chihuahua documents continuing basin inversion well into the Eocene.

Previous observations of spatial correlations between structurally complex basin margins and numerous major Cretaceous through Miocene mineral deposits are enhanced by the discovery of the large Cinco de Mayo polymetallic carbonate deposit hosted in stacked west-directed out-of-the-basin thrusting on the west margin of the Carrizal Basin.

Table of Contents

List of Tables

List of Figures

CHAPTER 1: INTRODUCTION

The foundation of this dissertation is more than thirty years of widespread reconnaissance and detailed field geologic studies in Mexico mostly focused in mineralized districts between 23° N Latitude and the international border (Fig. 1.1).

Starting with my masters field studies at Cerro de Mercado in 1971, much of the early work focused on the Eocene through Miocene Sierra Madre Occidental Volcanic Province of Mexico. In the 1990's, focus shifted to the distribution and structural controls of ore deposits in Mexico with increased interest in the Sierra Madre Oriental fold belts. For the past 25 years these investigations have focused more on the basement and Mesozoic strata of Mexico. Major projects mapped from 1991 through 2002 for Minera Kennecott included Cananea, Nacozari and Mulatos, Sonora and in southern Chihuahua to northern Zacatecas; the Chihuahua and Parral Districts through Mapimi and Sierra Ramirez, Durango to Concepcion del Oro, Zacatecas.

After achieving candidacy for the PhD program, mapping was carried out from 2006 through 2014, principally for MAG Silver Corporation. Mapping in north-central Chihuahua mapping covered from Samalayuca to Cinco de Mayo and into the Chihuahua District. Mapping in southwestern Chihuahua included Lluvia del Oro, Moris and Batopilas, Chihuahua and Sierra Ramirez and Salamandra, Durango Additional mapping was expanded to the areas surrounding project areas with reconnaissance mapping carried out along the many roads traveled to tie the more detailed areas together.

Much of the data generated by this work were inconsistent with existing tectonic models for the Mesozoic and older rocks underlying the Eocene through Miocene volcanic rocks, so alternative models that depart in significant ways from older models have been developed. Focusing on the details of Jurassic through Eocene structure, it became apparent that the Mesozoic basins could be best defined by understanding their tectonic history through a basin inversion model. Mapping distinctive out-of-the-basin thrusting along basin margins appears to greatly improve the spatial definition of the basins and suggests that the basin structural framework exerts important controls on the distribution of Mesozoic and Tertiary mineralization in Mexico. Early models of mineral distribution in northern Mexico focused mostly on magmatic controls; laterally in relation to the subducting margin and vertically in relation to vertical zoning of the volcanic pile and evolution of the magma systems over time. A few new dates help project the well-documented Laramide through Miocene sweeping of Mexico's volcanic arc back as far as the Jurassic and possibly to the Permo-Triassic.

OVERVIEW OF THE DISSERTATION

Understanding the distribution and boundaries of crustal provinces is crucial to understanding later tectonic development. Exposures of the basement in northern Mexico are very limited, so even a few new exposures are significant. This study focuses on the results of initial structural reconnaissance mapping over wide areas of northern Mexico, augmented by detailed mapping in selected areas that demonstrate a need to revise previous crustal tectonic evolution models for the region.

A new model of an Early to Middle Jurassic forearc basin resting on extended crust referred to here as the Mezcalera Basin, is proposed as most consistent with the observed distribution of basement and Mesozoic strata along Mexico's west coast. This is seen as evolving from a Late Jurassic intra-arc basin filled with deep water volcanic detritus-rich turbiditic strata through Early Cretaceous back arc deep shelf strata. Overthrusting of Jurassic-Cretaceous Mezcalera arc basin strata onto the Mexican craton along the western edge of the Central Highland of Mexico appears to indicate the limit of thinner Paleozoic (Ouachita Orogen) crust, whereas interpreted areas of thicker Proterozoic (Mazatzal) and possible Neoproterozoic (Pan African) crust occur in areas where overthrusting has not been recognized.

Previously, the distribution of the Triassic-Jurassic intracratonic basins in Mexico was defined by thickness variations and the distribution of basin, platform and shoreline facies as determined by stratigraphic studies. However, mapping of out-of-the-basin thrusting onto minimally deformed adjacent platforms and inverted basement blocks along basin margins not only more clearly locates the basin margins, but helps define the previously unrecognized Carrizal Basin in northern Chihuahua.

New radiometric dating of igneous rocks across northern Mexico helps expand the time over which the migration of volcanic arcs across the Mexican craton and its western marginal basin can be documented. Reconnaissance mapping of folds in rhyolite flows supported by one radiometric date demonstrates that tectonic shortening of the previously extended crust was active well into the Eocene.

Finally, the newly defined arc basin and redefined intracratonic basins are shown to display strong spatial associations with the Mesozoic and younger mineral deposits of the region. Basin inversion develops its most complex structures along the basin margins creating the greatest structurally induced permeability and favorability for magma emplacement along the basin margins. It is speculated that the greater permeability of the coarse clastic basin fill and chemistry of evaporites, marine shale and crust influence the chemistry and distribution of ore deposits within the basins as well.

Each chapter is presented formatted as a paper to publish. One paper "Geological and geochemical evidence of a Mesozoic marginal basin in western Mexico: Implications for regional ore genesis in the Guerrero Province", Lyons (2008) was published after an oral presentation at the 2007 Arizona Geological Society Symposium on "Ores and

Orogenesis: Circum-Pacific Tectonics, Geologic Evolution, and Ore Deposits". It is presented in the Appendix B.

HYPOTHESES TO BE TESTED

A number of hypotheses having major influence on understanding of the Mesozoic tectonic evolution of Mexico have been proposed over the past 40 years. One of the earliest of these hypotheses is the Mojave-Sonora Megashear (MSM), initially proposed by Silver and Anderson (1974) and Anderson and Silver (1979) as an explanation of an apparent discontinuity in lead isotopes patterns in northern Sonora. Another major hypothesis proposed by Coney and Campa (1983) attributed a major geologic discontinuity in the basement geology along the west coast of Mexico to the accretion of an oceanic arc (Guerrero Terrane) to western Mexico during the mid-Cretaceous.

Other hypotheses included the Jurassic tectonic emplacement of the distinct Caborca Terrane in northwestern Sonora as part of the MSM hypothesis (Anderson and Silver, 1979, 2005), the distribution of early Mesozoic intracratonic basins as related Late Jurassic pull-apart basins caused by North American plate rotation (Haenggi and Muehlberger, 2005), and Late Jurassic pull-apart basins at releasing bends in the MSM (Anderson and Nourse, 2005). Also included are several theories about the development of Sierra Madre Oriental fold belts such as northeastward translation of the Mesozoic limestone on an evaporite detachment plane producing thrusting and folding at the leading edge of the detachment fault (Marrett and Aranda-Garcia, 1999), and a combination of transpressional motion through the region along with evaporite tectonics (Haenggi, 2002).

The hypotheses proposed here and developed in the following chapters are based on integrating published studies with extensive reconnaissance mapping carried out in the states of Sonora, Chihuahua, Sinaloa, Durango, Coahuila and Zacatecas combined with widely scattered detailed studies usually dictated by mineral exploration.

Chapter 2 presents limited new data on the crust of northwestern Mexico that suggests (1) interpreting published (Housh and McDowell, 2005) ε_{Nd} data alone indicates a distribution that may better reflect basement provinces (2) distinguishing between high frequency aeromagnetic anomalies typical of layered volcanic rocks and low frequency anomalies that more typically reflect basement anomalies including stocks and batholiths helps recognize basement fabrics, and (3) reinterpreted and new metamorphic outcrops suggest a significantly larger area of Paleozoic crust underlying north-central Mexico.

Chapter 3 presents data that has led to three hypotheses related to Mexico's western Mesozoic margin (Fig. 1.2). The hypotheses include (4) a Jurassic through Lower Cretaceous marginal arc basin deposited along a rifted cratonic margin possibly formed during the Late Triassic to Early Jurassic, (5) the emplacement of the Caborca Terrane along a transpressional fault at the end of the Cenomanian and (6) the overthrusting of Jurassic and Lower Cretaceous marginal basin slope strata on to the Paleozoic crust of the central Mexican highlands. The last hypothesis of Chapter 3 is the development of a major inverted basement block along the east margin of the marginal basin (7) that explains the string of metamorphic basement outcrops from Parral, Chihuahua to Durango, Durango.

Chapter 4 presents data that has led to hypotheses related to the Mesozoic intracratonic basins of northern Mexico. These hypotheses include (8) bidirectional out-of-the-basin thrusting documents basin inversion as the primary driver of the Sierra Madre Oriental fold belts, allowing structural mapping to refine the definition of these basins (Fig. 1.2). (9) These refined basin margins allow the division of the Chihuahua Basin (Chihuahua Trough of common usage) as defined by Haenggi (2002) into two separate basins, the Chihuahua and the Carrizal. Mapping and dating of volcanic rocks led to the hypothesis (10) that Late Jurassic through Early Cretaceous arc magmatism needs to be incorporated into arc migration models of western Mexico that formerly displayed a gap between the Middle Jurassic Nazas Arc and the Late Cretaceous Tarahumara Arc. Finally, spatial correlations between ore deposit occurrences and the better-defined Mesozoic basins leads to hypothesis (11), which suggests possible influences of these basins on mineralization distribution in northern Mexico with the structural margins of intracratonic basins providing a favorable plumbing for fluids and magmas related to ore deposition and crustal and basin fill chemistry of the western marginal basin appearing to influence ore deposit content within the basin..

The following is an elaboration on these hypotheses.

(1) **Utilizing ε_{Nd} alone to interpret basement provinces**

Farmer and DePalo, (1983, 1984) recognized that between ε_{Nd} and Sr isotopic compositions ε_{Nd} was less prone to anomalies resulting from crustal structure rather than age. They cited peeling off of lithospheric crust as one cause of anomalous Sr isotopic ratios (they gave an example of NW Utah) and potential contamination is observed in the widespread carbonate hosted strontium deposits observed in the Lower Cretaceous carbonates during this study. Farmer and DePalo also discussed the mobility and contamination of reworked lead as some of the shortcomings of Pb data. The J-lead issue of southeast Missouri being one example of hydrothermally derived lead being a mix of old and young lead isotopes. From these observations the ε_{Nd} was chosen to re-evaluate the data from Housh and McDowell (2005) as a signature of basement age. The resulting data fields are believed to better reflect crustal provinces.

(2) Use of visual filtering of high frequency and low frequency aeromagnetic data to interpret sub-volcanic geology.

Acquiring aeromagnetic data at two different elevations allows for distinguishing between deeper seated anomalies and shallow anomalies. The same effect but less reliable can be achieved mathematically by the process of upward continuation of the data. This entails using measurements from one constant elevation and calculating what the value is expected to be if measured at a higher elevation. Both of these processes allow removal of the high frequency data that is often the product of variably exposed stacked magnetic reversals in a volcanic pile.

Using observation (the human brain has proven well adept at recognizing visual spatial variations), the same results can be achieved. The broader and long linear aeromagnetic features can be traced across the boundaries of volcanic fields, while a large percentage of the fine scale disconnected anomalies are found to be mostly restricted to within volcanic fields. Actual field measurements have shown that the high frequency aeromagnetic anomalies reflect the stacked, constantly reversing polarities of volcanic strata on a topographically complex surface.

(3) Broad extent of Paleozoic crust in north-central Mexico

New and reinterpreted published data documented in Chapter 2 suggests that the metamorphism of the Paleozoic strata accumulated offshore of Laurentia and Gondwana during the Permo-Triassic Ouachita suturing of these continents produced new continental crust found from the southern edge of the North American Laurentian craton across the Coahuila platform into northern Zacatecas and westward into central Durango.

The extent of the Mezcalera overthrust discussed in Chapter 3 is interpreted as reflecting the thinner less-buoyant nature of this younger crust.

(4) Possible Mesozoic Extensional Margin and Subsequent Marginal Arc Basin.

New field data integrated with published data presented in Chapter 3 suggest that extension along the west coast of Mexico began during the Late Triassic-Early Jurassic (Keppie and others, 2006; Mauel and others, 2011). Oceanic plate rollback and asthenospheric rise during rollback would induce extension and will be discussed as a possible hypothesis integrating the observed extensional tectonic environment and arc migration. Because of the apparent complex history of the basin, it will be here named the Mezcalera Marginal Basin after both the Mezcalera Group that makes up the overthrust of its strata onto the craton and the Mezcalera Ocean that was proposed (Dickinson and Lawton, 2001) to separate the hypothetical pre-accretionary Guerrero Arc from the craton.

The Mezcalera Marginal Forearc Basin first accumulated non marine continental strata during the Early Jurassic extensional stage (Mauel and others, 2011). Later it was overlain by volcaniclastic-rich marine and turbiditic strata deposited after marine flooding and coincident volcanism during the Middle to Late Jurassic (Gonzalez-Leon and others, 2009 and Mauel and others, 2011). Two different facies overlie the deep water Upper Jurassic strata from the Early Cretaceous to the Late Cenomanian, the alluvial fan and deltaic complex of the Bisbee Group variably reworked by the marine incursion that deposited the Bisbee Group Mural Formation carbonate strata and the distal turbidites of the neritic shelf strata deposited south of the deltaic complex. The turbiditic slope strata were observed at the Gochico Mine, Sonora (Rosas, 1991 and this study) and at Chirimoyo, Durango (this study).

The recognition of an early Mesozoic extensional margin and subsequent marginal basin in northwestern Mexico brings a new perspective to Mexico's northwestern continental margin geology, and projects the concept of the Arperos basin (Martini and others, 2012) from the southern Guerrero Province into southern Arizona. Both the Mezcalera and Arperos basins are now modeled to have similar cratonic affiliated origins (Archean through Jurassic detrital zircons now known in Batopilas strata) overprinted by extension produced by plate rollback during the Late Jurassic.

The accretionary Guerrero Terrane model will be reevaluated in light of recognition of a large marginal clastic wedge containing continental detrital zircons occupying a significant portion of its proposed distribution area, and new evidence of the migration of the continental margin arc across the formally proposed accreted material and evidence that transpressional motion has significantly affected the region. An apparent westward migration of the arc by accretion would require multiple accretion events and lack the extensional environment needed to produce extension east of the arc system.

(5) Cenomanian Emplacement of the Caborca Terrane by Transpressional Motion.

Definition of the Mesozoic Mezcalera marginal basin and its tectonic history suggests alternative models of emplacement of the Caborca Terrane. The trans-Mexican Mojave-Sonora Megashear hypothesis is placed in doubt because the basin geometry indicated by Jurassic and Lower Cretaceous outcrops displays no significant offset consistent with that model. The apparent separation of the Caborca Terrane from the North American Craton by the Papago-Cucurpe-Arivechi-Moris-Batopilas-Asperos composite basin now proposed as the Mezcalera Marginal Basin implies that the Caborca Terrane was either part of the west side of the Upper Triassic rift valley (Dickinson and

Lawton, 2001) later thrust back against and over the Mezcalera basin strata or that it was emplaced by transpressional migration to the current location following the deposition of Jurassic and Lower Cretaceous strata.

Thrusts of Caborca basement from Cucurpe (Mauel and others, 2011) to Opdepe-Creston, Sahuaripa (Pubellier and others, 1995) over the Upper Jurassic Cucurpe Formation and equivalents, and Lower Cretaceous Bisbee Group document a major shortening event in the Late Cenomanian. Reconnaissance mapping during this study projects this thrusted boundary between Caborca and the Mezcalera Marginal Basin south to Gochico, Sonora; where Bisbee Group correlative strata are thrust over Mezcalera basin strata at Zataque, Sonora-Sinaloa; and Lluvia del Oro, Chihuahua. Ordovician strata exposed at El Fuerte, Sinaloa (Vega-Granillo and others, 2018, 2011) may be a basement block within the Mezcalera Basin or an exposure of the basement west of the proposed transpressional fault. Upper Jurassic basin strata are located at Moris and Batopilas, Chihuahua and Lower Cretaceous slope strata crop out at Gochico, Sonora and Chirimoyo, Durango east of the thrusting.

Then there is the observation that the Triassic Barranca Group appears to be sourced from the Mazatzal Province farther north than its present location (Gonzales-L. and others, 2009), with the possible offset of distal Bisbee Group south of its depocenter in northern Sonora to the junction of Sonora, Sinaloa and Chihuahua (this study). This appears to be a simpler interpretation than proposed (Vega-Granillo and others, 2007; Talavera-Mendosa and others, 2007) for the migration of the Paleozoic Acatlán Complex to southern Mexico combined with the thrusting documented along the west boundary of the Mezcalera Marginal Basin. All are indicative of tranpressional motion along the west boundary of the Mezcalera Marginal Basin. Dating of the thrusting event along the east side of the Caborca Terrane as Cenomanian comes mostly from the studies of Cucurpe (Mauel and others, 2011) and Sahuaripa (Pubellier and others, 1995) among others.

(6) Timing of the Mezcalera Overthrust

The Mezcalera overthrust can be demonstrated to have been emplaced both by the repeated Jurassic through Early Cretaceous ages of deep marine turbidites overthrusting similar age of autocthonous platform strata of the lower plate of the thrust and the timing of carbonate and schist bearing debris flows from the Lower Cretaceous platform carbonates within the Late Cenomanian-Early Turonian Indidura Formation. Overthrusting of Jurassic and Lower Cretaceous marginal basin slope strata onto the Jurassic and Lower Cretaceous platform strata are documented in PEMEX drill hole Parral-1 (Grajales Nishimura and others, 1992). Mapping at Indé, Durango for this study and various published maps (Munguia-Rojas. and others, 1998, 2000) document the Paleozoic crust underlying the central Mexican highlands being uplifted in inverted basement blocks along the east boundary of the Mezcalera Marginal Basin exposed to the west in the deep canyons cutting the Sierra Madre Occidental Volcanic Province rocks.

This indicates major cross-basin shortening of the Mezcalera Marginal Basin that thrust the Mezcalera Group onto the platform during the Cenomanian. Limestone and schist-clast debris flows in the Cenomanian Indidura Formation observed during this study suggest uplift and exposure of Lower Cretaceous or older limestone and Paleozoic basement concurrent with Cenomanian-Turonian Indidura deposition directly on an inverted basement block of Paleozoic schist capped with Jurassic Nazas Formation in the Durango City area. This closely fixes the timing of shortening to the Late Cenomanian or Early Turonian.

The presence of Lower Cretaceous platform carbonates below the Upper Jurassic through Lower Cretaceous shelf, slope and rise strata of the Mezcalera group in PEMEX drill hole Parral-1 (Grajales-Nishimura. and others, 1992) clearly documents the overthrust over platform relationship of the Mezcalera Group.

(7) Belt of metamorphosed basement from Parral, Chi. to Durango, Dgo. defines an inverted basement block

The belt of metamorphic basement outcrops that is observed west of Parral, Chihuahua at Valle de Olivas, and continues south-southeast through Santa Maria del Oro, on to, Inde and SanLucas del Ocampo has now been projected near to Durango City in a drill hole at the Salamandra Prospect 36 km ENE of Durango City. This series of occurrences is hypothesized to be an inverted basement block developed after initial thrusting of the Mezcalera Thrust. Evidence and timing of uplift is documented in debris flows of limestone and schist of the Indidura Formation and it exposes the Paleozoic crust that underlies much of northern Zacatecas, southern Coahuila and eastern Durango.

(8) Late Cretaceous to Eocene shortening of intracratonic basins

The tectonic shortening that initiated in Mezcalera basin and produced the Mezcalera Overthrust migrated eastward throughout the Late Cretaceous into the Eocene and produced the basin inversion that resulted in the Sierra Madre Oriental Fold Belts. West-southwest to south southwest-directed thrusting delineates the west and south sides of the newly defined Carrizal Basin at Sierra Santa Lucia and Sierra Mojina, Chihuahua, and the Mexican Basin at San Fermin and Sierra Ramirez, Durango.

The east sides of these basins are delineated by east-northeast thrusting out of the basins at Sierra Banco Lucero and Division del Norte, Chihuahua and Bermejillo-Mapimi, Durango. All of these locations were mapped during this study. The basin inversion timing is constrained to be still in progress at 43 Ma by a U-Pb date of a folded rhyolite flow at Division del Norte; other folded volcanic rocks were observed in the Sabinas Basin northeast of Hercules, Coahuila and limestones are thrust over volcaniclastic debris at Adargas, Chihuahua just south of Jiménez, Chihuahua.

(9) Division of the Chihuahua basin into two distinct basins the Chihuahua and Carrizal

Reconnaissance and detailed mapping north of Chihuahua city documented bidirectional thrusting out of the intracratonic basins. Tight folds, repeated stacked thrust sheets, along with inverted basement blocks were often observed on the trench side of the basins whereas simpler long ramp thrust faults are documented in earlier studies in the El Paso, Texas area and on the south side of the Coahuila Platform (Garza, 1973). The documentation of out-of-the-basin thrusting on all studied basin margins produced better delimited basin distributions and led to the recognition that the Chihuahua Basin is actually two distinct basins separated by a basement ridge from the Florida Mountains of New Mexico to the Aldama area north of Chihuahua City.

(10) Carrying the sweeping arcs back to the Middle Jurassic and Triassic.

Additional measured and interpreted ages of volcanic rocks of the region suggests carrying the model of sweeping arc axes from the Late Cretaceous back to the Middle Jurassic and possibly back to the Permian. From published data (Torres and others, 1999; Garza, 1973) a Permo-Triassic arc appears to move westward into the east edge of the Nazas Arc in north central Mexico. There appears not to be enough data to relate how the Permian arc would have initiated after the fusion of Gondwanaland to Laurentia forming the Ouachita-Marathon suture zone. It is possible that the Pacific floor was subducting under Laurentia and Gondwana and after their fusing one continuous arc resulted.

Published data supplemented by this study indicates the Nazas Arc continued sweeping westward in central Mexico during the Early and Middle Jurassic reaching the Mezcalera Marginal Basin in the Late Jurassic. This sweep appears to continue westward into the Early Cretaceous until reaching its western most position as the Alisitos Arc. At the end of the Cenomanian the arc began sweeping eastward through the Tarahumara and Laramide Arcs from where it continues in its well documented (Damon and others, 1981; Clark and others, 1982) sweeping to the northeast before returning westward to the Sierra Madre Occidental Province.

(11) Association of Mineralization with Mexican Mesozoic Basins

The intracratonic basin-ore deposit model as applies to Mexico evolved from two independent studies. Megaw (1988) and Megaw and others (1996) focused mostly on the ore deposits but emphasized the common spatial association of these deposits with the published basin definitions. This study (Lyons, 2002, 2008) has focused more on mapping and understanding the basin margin faults that exert direct structural control over the flow of ore forming fluids and influence the emplacement of magmatic heat engines at depth. From these studies, refined definitions of the basin margins further constrain the spatial correlation between mineralization and the basins. In 2006 the extensive ore deposit knowledge of Megaw and the structural mapping experience of the author were combined to test the model with mapping and follow up drilling during the successful exploration program at the previously minor Cinco de Mayo District in north central Chihuahua.

The west coast parallel belt of gold deposits is a feature of Mexican ore deposit distribution widely discussed in the mineral exploration industry. As the distribution of the Jurassic marginal basin began to be understood, it became clear that there is a spatial association between the gold belt and the marginal basin. This association is discussed in the attached paper (Lyons, 2008) from the perspective of a number of elements such as boron, molybdenum and cobalt that correspond to the same gold belt and what common geologic environment this suite of elements might signify.

APPROACH TO TESTING HYPOTHESES

The understanding of the marginal basin model is still evolving as mapping provides opportunities to collect more data on which the model is being built. Structural mapping, stratigraphic correlations, interpretations of aeromagnetic data and radiometric ages are still very useful tools in this region. Logistical challenges make collecting data in Mexico, particularly the marginal basin area, very difficult. As more mapping opportunities present themselves, the model will continue to evolve.

Field mapping both at regional and mining-district scales coupled with an understanding of how the mapped structures developed constitute the foundation of this study. Mapping of fault bend folds and fault propagation folds are fundamental indicators of relative direction of motion between two faulted plates (Woodward, Boyer and Suppe, 1989). Regional maps in this study indicate upper plates of out of the basin thrusting with the standard teeth on the upper plate. Thrusting direction of the upper plates onto adjacent platforms as determined mapped thrusting directions are indicated by arrows on the platforms.

The first regional study resulted in a reconnaissance map of nearly three quarters of the state of Sonora. Early mapping focused on evaluating the favorability of possible structural splays of the Mojave-Sonora Megashear as sites for mineralization. The major mapped structures were found to be sealed with extensive impermeable gouge along the major fault segments observed, but peripheral structures with much less movement appeared to be more permeable and thus more favorable for the transmission of mineralizing fluids.

Although the location of the proposed Mojave-Sonora Megashear was never constrained by field relationships, many other structures and associated exploration targets were observed that required new hypotheses to explain their presence and apparent motion. Reconnaissance mapping was continued in the Chihuahuan Desert and Mesa Central highlands of Mexico with more detailed mapping in known and potential mineral districts (Fig.1.1).

Mapping in southern Mexico focused on individual districts and was not expanded into regional studies. While the district-scale mapping in southern Mexico appears to support the tectonic model presented here, the lack of regional reconnaissance mapping made it prohibitive to integrate them into a regional model at this time.

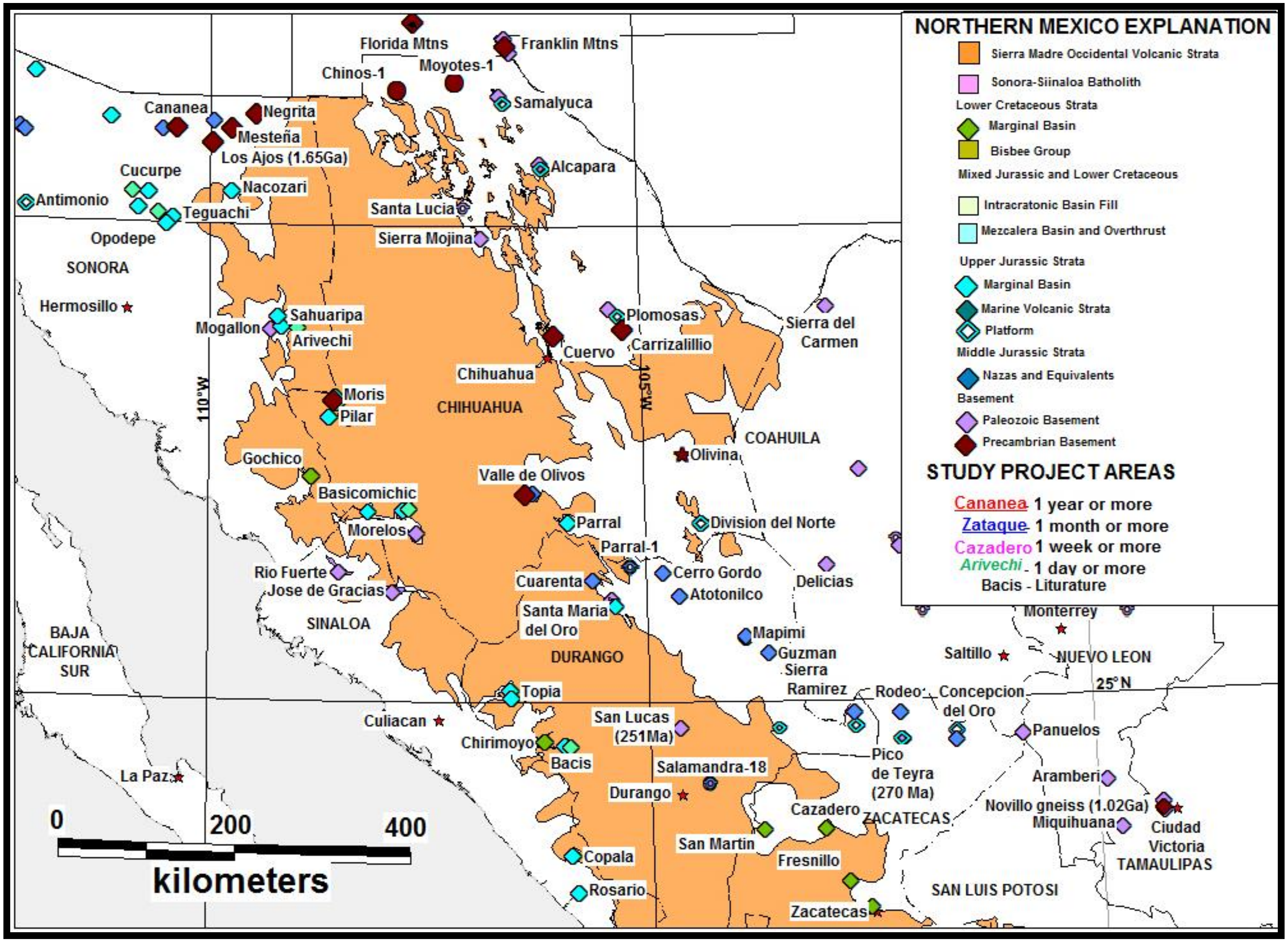
U-Pb dates on zircons from igneous and detrital sources, the principal analytical technique used in this study, assist in developing a time line on which to integrate the widely dispersed outcrops into the tectonic model. U-Pb dates are based on analysis of approximately 30 zircons from igneous rocks and approximately 100 zircons when available from Mesozoic and Paleogene sandstones and tuffs. One Re-Os date was obtained from Batopilas molybdenite to constrain the possible association with the local magmatic events.

SIGNIFICANCE OF THIS STUDY

A satisfactory demonstration of the hypothesis that the western margin of Mexico represents a late Paleozoic to Middle Jurassic extensional margin, developed behind the subduction zone, which was then mostly buried by Upper Jurassic through Lower Cretaceous marginal basin strata seriously conflicts with two widely accepted hypotheses for the tectonic evolution of northern and western Mexico: the Mojave-Sonora Megashear and accretion of the Guerrero Terrane. The successful discrediting of these hypotheses necessitates a major re-evaluation of the tectonic models of Mexico. The widely accepted Mojave-Sonora Megashear hypothesis requires hundreds to more than a thousand kilometers of left lateral displacement across Mexico, that data from many published studies and this study do not support. Further, the construction of most of Mexico west of the Sierra Madre Occidental Volcanic belt by mid-Cretaceous accretion of oceanic arcs to the western margin of Mexico is countervailed by field evidence for a normal marginal arc basin. The potential for some translational motion in northern Sonora remains but more as a coast-parallel transpressional motion than a cross-continent transform motion as proposed for the Mojave-Sonora Megashear. The demonstration of the presence of a significant Jurassic through Lower Cretaceous marginal basin along Mexico's western margin overprinted by a subduction-derived arc that swept across it, greatly diminishes the need for accretion to explain the tectonic construction of this part of Mexico. Thus the previously proposed Guerrero Terrane would become more properly an in-place marginal basin, the Guerrero or Mezcalera Province. Accretion is still a viable model for some regions of Mexico's western margin but on a smaller scale, particularly in Baja California where no mapping was done for this project.

Basin inversion has been proposed as a possible tectonic model for the development of the Sierra Madre Oriental fold belts in northern Mexico (Haenggi, 2001), but it has not been demonstrated by structural mapping. Other models such as regional detachment sliding (Marrett, 1999) have also been proposed. The reconnaissance and detailed mapping to be documented here confirms basin inversion as the primary tectonic mechanism for the northern Mexican fold belts but as expressed as bidirectional thrusting out of the basins produced by partial closing of the originally extended crust that produced the basin forcing the basin fill out of the basins in two directions parallel to the compressive forces. There is an asymmetry observed in the shortened basins such inverted basement blocks along the western and southern intracratonic basin margins closest to the continental subducting margin and lower angle thrusting, ramping on to the adjacent basement furthest from subduction.

Beyond the important scientific significance of a redefined tectonic model for Mexico, mineral exploration already has benefitted with the discovery of major deposits at Cinco de Mayo and potentially may benefit by further discoveries, from this evaluation of the apparent correlation of basins and their margins with important mineral deposits of Mexico. This model could also potentially influence global exploration concepts. Arc related extensional regimes similar to Mexico, encircle the Pacific basin and a focus on refining the understanding of these marginal basins and intracratonic basins with more precision allows a potentially more useful comparison between the distribution of the basins and the occurrence of ore deposits in northern Mexico with similar terranes found elsewhere particularly around the rim of the Pacific Basin.



NORTHERN MEXICO EXPLANATION
Sierra Madre Occidental Volcanic Strata
Sonora-Siinaloa Batholith
Lower Cretaceous Strata
Marginal Basin
Bisbee Group
Mixed Jurassic and Lower Cretaceous
Intracratonic Basin Fill
Mezcalera Basin and Overthrust
Upper Jurassic Strata
Marginal Basin
Marine Volcanic Strata
Platform
Middle Jurassic Strata
Nazas and Equivalents
Basement
Paleozoic Basement
Precambrian Basement
STUDY PROJECT AREAS
Cananea 1 year or more
Zataque 1 month or more
Cazadero 1 week or more
Arivechi 1 day or more
Bacis - Liturature
Florida Mtns
Franklin Mtns
Chinos-1
Moyotes-1
Samalyuca
Cananea
Negrita
Mesteña
Los Ajos (1.65Ga)
Alcapara
Cucurpe
Nacozari
Antimonio
Santa Lucia
Teguachi
Opodepe
Sierra Mojina
SONORA
Hermosillo
Plomosas
Sierra del Carmen
Sahuaripa
Mogallon
Arivechi
Cuervo
Carrizalillio
Chihuahua
110°W
105°W
Moris
Pilar
CHIHUAHUA
COAHUILA
Olivina
Gochico
Valle de Olivos
Basicomichic
Morelos
Parral
Division del Norte
Parral-1
Rio Fuerte
Cerro Gordo
Delicias
Cuarenta
Jose de Gracias
Atotonilco
SINALOA
Santa Maria del Oro
Monterrey
BAJA CALIFORNIA SUR
Mapimi
Guzman
Sierra Ramirez
Saltillo
NUEVO LEON
DURANGO
25°N
Topia
Rodeo
Concepcion del Oro
Culiacan
San Lucas (251Ma)
Panuelos
Chirimoyo
Pico de Teyra (270 Ma)
Bacis
Salamandra-18
La Paz
Aramberi
Durango
Novillo gneiss (1.02Ga)
0
200
400
Cazadero
ZACATECAS
Miquihuana
Ciudad Victoria
TAMAULIPAS
kilometers
San Martin
Copala
Fresnillo
Rosario
SAN LUIS POTOSI
Zacatecas

Figure .1.1

Figure 1.1 Map and explanation of northern Mexico shows mapping areas that have been incorporated into this study.

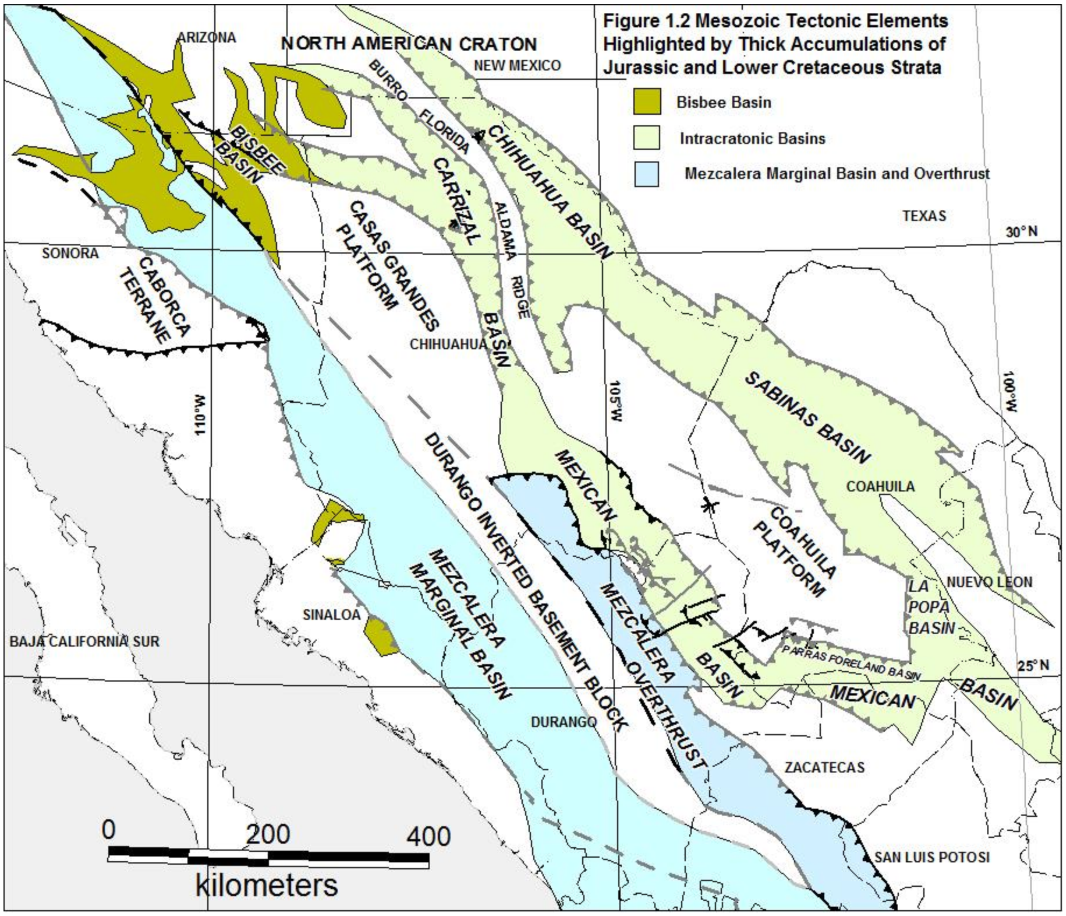


Figure 1.2. Tectonic map of northern Mexico derived from integrating mapping of this study with published studies referred to in text.

The Upper Cretaceous through Neogene volcanic rocks are removed. The light blue represents the strata and contemporaneous marine volcanic rocks that fill the Late Jurassic through Early Cretaceous Mezcalera (Guerrero) marginal basin along a Triassic or Jurassic rifted margin. The light blue belt to the east is an overthrust sheet of these same strata thrust onto the Paleozoic (Ouachita) age craton. The light green represents the intracratonic basins of northern Mexico as defined by the stacked thrusting, inverted basement blocks and mass wasting off of the elevated deformed ranges formed during the inversion of these basins from the late Cenomanian through the Eocene. The green-brown represents the Upper Jurassic-Lower Cretaceous Bisbee Group marine reworked deltaic complex with a distinctive Aptian-Albian limestone marker: the Mural Limestone. The Bisbee Group is defined along the borders of Arizona and Sonora and persists into New Mexico and Chihuahua, but isolated outcrops occur from the Sonora-Sinaloa border into central Sinaloa.

CHAPTER 2: PRECAMBRIAN AND PALEOZOIC BASEMENT OF NORTHERN MEXICO

The crustal foundation on which tectonic activity is proceeding can have a profound influence on the results. Thus the crustal foundation needs to be established before delving into the understanding of the causes of observed tectonism.

INTRODUCTION AND PREVIOUS WORK

The principal elements of the northern Mexican crust (Fig. 2.1) are the Proterozoic Mazatzal Province (1.65 Ga) mapped from Arizona and New Mexico into northern Sonora and Chihuahua, the Granite-Rhyolite Province (1.2 to 1.5 Ga) spanning from Missouri through Texas and into Chihuahua, and the Grenville Province (1.0 to 1.2 Ga) from eastern North America through Texas and into Chihuahua. All basement outcrops and dated drill intercepts of central Mexico between the Grenville age Cuervo and Carrizalillo (Blount,1983, 1993) outcrops east of Chihuahua City and the Novillo Grenville-age granulite outcrop 20 km west of Ciudad Victoria, Tamaulipas, are known to be or can be interpreted as being Paleozoic Ouachita age crust.

Early mapping of basement distribution consisted of regional field studies in southern Sonora (King, 1939) and the Coahuila Platform (King and others, 1944). Maps from many mining districts produced initial structural studies such as at Concepcion del Oro (Rogers and others, 1956) and at Cerro Cuervo (Handschy and Dyer, 1987). Radiometric dates on outcrops and PEMEX basement intercepts have been compiled by Lopez-Infanzon (1986), Wilson (1990), and Grajales-Nishimura and others (1992). Isotopic analyses of igneous rocks cutting the basement of Sonora by Silver and Anderson, 1974, and in Chihuahua by Cameron and Cameron (1985), James and Henry

(1993) and Housh and McDowell (2005) were used to interpret the configuration of covered basement.

Authors tend to interpret geometries differently for the various provinces. Some authors project the Granite-Rhyolite Province into Chihuahua (cf. Karlstrom and others, 1999), whereas others do not project it into Mexico at all (Amato and others, 2008). An ongoing issue highlighted by these authors is whether the Granite-Rhyolite Province is a crustal province or only a supracrustal volcanic province fed by granites and only minimally deformed by the Grenville tectonic event. Sm-Nd isotopic studies (Rohs and Van Schmus, 2007) indicate that Granite Rhyolite Province magmatism reflects two different older underlying provinces.

Variously interpreted Paleozoic Ouachita age strata underlie the central highlands of Mexico at Las Delicias, Coahuila (King and others, 1944; McKee and others, 1988), Pico de Teyra, Zacatecas (Cordoba, 1964; Anderson and others, 2005b) and the Granjeno Schist in western Tamaulipas (Barboza-Gudiño and others, 2011). Along the western margin of the central highlands a northwest-trending belt of Paleozoic schist (Fig. 2.1) crops out at Santa Maria del Oro (~325 Ma Mississippian; Lopez-Infanzon, 1988) and San Lucas del Ocampo, Durango (~250 Ma Permian; Iriondo and others, 2003). The Zacatecas Formation was first identified as Paleozoic and then Triassic (Burkhardt, 1906), but detrital zircon ages (Escalona-Alcazar and others, 2009) indicate it is Lower Cretaceous. Some recent concern about the precision of mapping has been expressed on the detrital zircon dates (Lawton, personal communication). Mapping soon to be published (Ortega-Flores and others, in press) indicates more complex geology with much smaller outcrops of Triassic in the Zacatecas City area. Field reconnaissance in the area during this study was inconclusive. Pico de Teyra, Zacatecas (Fig. 1.1) was reinterpreted as Triassic (Anderson and others, 2005) despite the youngest zircon being

Permian (Diaz-Salgago and others, 2003) and abundant Triassic magmatism being documented in the area (Garza, 1973). Grenville age (1.0 to 1.25 Ga) granulites crop out within the Paleozoic schist 20 km west of Ciudad Victoria, Tamaulipas (Fig. 2.1), and similar age xenoliths occur in young Tertiary basaltic vent complexes (Olivina, Chihuahua, Fig.1.1). This is interpreted as evidence of an underlying Grenville age crust called Oaxaquia by Ortega-Gutierrez and others (1995). The extensive low grade schist with an east northeast to northeast striking metamorphic fabric (Barboza-Gudiño. and others, 2011) is consistent with documented Ouachita age fabric developed in the Paleozoic between the Grenville age outcrops at Cuervo and Carrizalillo, Chihuahua and the first outcrop larger than a xenolith, of Grenville age basement, the Novillo Gneiss at Ciudad Victoria. The extensive shortening in the Paleozoic rocks with no exposures of older basement implies that no convincing argument can be made that this is a region underlain by older Grenville age basement. The dated xenoliths may only represent debris from the adjacent Grenville age crust along with the significant Grenville age zircons documented in the Paleozoic Granjeno schist (Barboza-Gudiño and others, 2011).

Smaller basement elements such as Caborca and Cortez comprise the remainder of the basement in western Sonora. Although the basement outcrops are more extensive in this area than most of Mexico, there are many models explaining the distribution of the various ages of basement. The earliest model (Silver and Anderson, 1974) used Pb isotope studies to explain the emplacement of older Yavapai and Mojave crust (1.8 to 1.7Ga) of the Caborca Terrane against younger Mazatzal crust (1.7 to 1.6Ga) of the southern edge of the North American craton by a major left lateral transcurrent fault, the Mojave-Sonora Megashear. The most recent model using a denser distribution of isotopic data to wrap the Yavapai and Mojave crust around the Mazatzal crust during the accretion of Mazatzal crust to the Yavapai belt (Iriondo and others, 2010).

Haxel and others (1980, 1984) recognized an area of south-central Arizona that lacked autochthonous pre-Jurassic rocks that projects into Sonora (Anderson and Silver, 1979). Further mapping, and studies have projected the Papago Terrane of Haxel south into the Cucurpe, Sonora area (Calmus and Sosson, 1995; Mauel and others, 2011). Calmus and Sosson (1995) project the Papago Terrane farther west than Haxel and others (1984), but the Calmus and Sosson model extends the province over Precambrian basement that is inconsistent with Haxel's original Papago definition of a region without evidence of crust older than Jurassic. Pre-Jurassic basement rocks from the Caborca Terrane appear to be thrust over both the Upper Jurassic Cucurpe deep marine strata and the Lower Cretaceous Bisbee Group. A distinct characteristic of the structural boundary between the Papago Terrane of Haxel and the Caborca Terrane observed by various authors is the thrusting of the Proterozoic basement and strata of Caborca over both the Jurassic and the Lower Cretaceous strata in Arizona, (Haxel and others, 1980, 1984), Cucurpe, Sonora (Mauel and others, 2011), Creston, Sonora (Valenzuela-Navarro and others, 2003, 2005) and Sahuaripa, Sonora (Pubellier and others, 1995). Folding and thrusting of Jurassic and Lower Cretaceous strata occurs throughout the Papago Terrane but on the North American craton to the east the structural style changes to high angle reverse faults and associated deformation.

The Guerrero Terrane (Sonora, Sinaloa, Chihuahua, Durango, Jalisco, Michoacán and Guerrero) is interpreted in the literature as an accreted terrane (Campa and Coney, 1983; Centeno-Garcia. and others, 1993; Dickinson and Lawton, 2001) that underlies much of Mexico's western margin.

PROTEROZOIC

The Proterozoic basement of northern Mexico is best exposed in the high angle reverse faulted basement blocks of northeastern Sonora. In this area, outcrops of the Paleoproterozoic Pinal Schist of the 1.65 Ga Mazatzal Province are identical in appearance to those in Arizona. The Granite-Rhyolite Province (1.3 to 1.5 Ga) crop out only as granites, mostly emplaced into the Mazatzal basement as 1.44 Ga anorogenic granites. Other younger Proterozoic orogenies are represented in Chihuahua. Grenville age (1.1 Ga) rocks crop out at Cuervo (Los Filtros) and Carrizalillo in east central Chihuahua and at the 1.0 Ga Novillo Gneiss west of Ciudad Victoria, Tamaulipas. The largest area of exposed Proterozoic is in northwestern Sonora in the Caborca Terrane with rocks equivalent in age to the Yavapai (1.75 Ga) of Arizona and Mojave (1.8 Ga) of Arizona and California.

Mazatzal

The 1.6 to 1.7 Ga Mazatzal basement is only known in northeastern Sonora as an extension of the province in southern Arizona that continues into Sonora. Pinal Schist that comprises a major part of the Mazatzal Province of southern Arizona continues into northeast Sonora with outcrops observed northwest of the Cananea District south of the Mariquita Mine and on southwestern slopes of the Sierra los Ajos 35 km to the east-southeast of Cananea. On the east side of Sierra de los Ajos a K-Ar date of 1640 Ma was reported at Mesteñas (Garcia-Cortez and others, 2003). In addition to other formations of the Mazatzal, numerous occurrences of the 1.44 Ga anorogenic rapakivi-textured granite and equivalent stocks and batholiths are found cutting the Mazatzal Group and older Precambrian basement. A new occurrence of granite cutting a gneiss at Moris, Chihuahua was dated at 1.44 Ga in this study (see data in Appendix A).

Detrital zircons from the Lower Cretaceous Las Vigas Formation were studied in two different localities 30 km apart. A sample was taken at a Sierra Santa Lucia (Cinco de Mayo), Chihuahua core hole CM10-247 (304,158E, 3,339,942N UTM NAD 27 Mexico Zone 13R) (JL-CM-V1, see Appendix A) and at an outcrop on the east side of Sierra Mojina, Chihuahua (JL-MJ-V1, 323,377E, 3,305,496N, 13R, NAD 27, see Appendix A). It should be noted that all UTM data is in the North American Datum (NAD) 27 because in Mexico, all mineral claim data has been recorded this way and it was considered prohibitive to convert the important historical data to a newer system. Both samples came from between the base of the Upper Aptian Cuchillo Formation and the top of regionally propylitically altered Permian Scherrer Formation arkose. From the Cinco de Mayo drill hole several meters of sandstone were sampled that made up the whole thickness of the Las Vigas, and at Sierra Mojina one sample of schist-fragment conglomerate was sampled out of approximately 150 meters of similar rock.

The Cinco de Mayo sample (Fig. 2.2) is dominated by Mazatzal age zircons (53/100 within 1600 to 1700 Ma with a peak at 1.65 Ga, Figure 2.3). The nearest current Mazatzal outcrops are over 200km to the north and northwest. The second largest populations are Pan-African zircons (13/100 within 645 to 702 Ma) and Granite-Rhyolite Terrane zircons (13/100 within 1420 to 1585 Ma). The period between 1700 to 2000 Ma (Yavapai and Mojave) is represented by eight dispersed zircons. There are three Permo-Triassic zircons (245 to 255Ma) consistent with dating of individual igneous clasts from Sierra Mojina (Denison and others, 1971), one earliest Cretaceous zircon (138 Ma slightly older than assumed age of deposition) and one Archean zircon (2.986 Ga). The Cinco de Mayo Las Vigas sample consists of a clean quartz sand and conglomerate resting on propylitically altered Scherrer arkosic mudstone, sandstones and conglomerates. There is a high probability that at least some if not all of these zircons are derived from the Scherrer representing at least one generation of reworking.

Granite Rhyolite Terrane

The 1.3 to 1.5 Ga Granite-Rhyolite Province crops out as rhyolitic welded tuffs, flows and volcanoclastics cut by comagmatic granites in the Saint Francis Mountains of southeast Missouri. For many years this province has been recognized as mostly a supracrustal province (Karlstrom and others, 1987) resting older crust with some Grenville age deformation overprinted (Van Schmus and others, 1996).

At the base of the eastern face of Sierra Mojina, a mostly homogeneous meta-rhyolite schist-dominated conglomerate of the Las Vigas Formation was mapped. A sample was collected for U-Pb radiometric dating of detrital zircon grains. Detrital zircons from the Sierra Mojina Las Vigas outcrop contain an almost continuous distribution of zircon ages from 1038 Ma to 1570 Ma (Fig. 2.2, and see Appendix A for data). Granite-Rhyolite Province age zircons (1300 to 1500 Ma) make up a third of all zircons (35/98 zircons), Grenville age zircons (1000 to 1250 Ma) account for another third (35/98) and Late Paleoproterozoic zircons between 1700 and 2070 Ma consist of one fifth of the total (20/98). A Pan-African igneous event is reflected by four zircons with an age range of 744 to 857 Ma. An unusual cluster of three zircons come from the Late Cambrian to the beginning of the Ordovician (444 to 499 Ma) was also observed. An earlier poorly constrained Rb-Sr date from Denison and others (1970) focused on sparse igneous clasts and yielded a Permian age consistent with two Permo-Triassic zircons from the detrital zircon sample at Sierra Mojina. The monolithic nature of the conglomerate clasts suggest a single source of zircons, but the multiple ages represented in the U-Pb data suggest that there are multiple sources. A nearby Granite Rhyolite

Province occurrence is interpreted as one source for the clast and sand, and a sandy matrix including zircons either from Grenville and possibly Pan African coming from more distant he south or all grains other than the Granite Rhyolite being coming from the nearby Scherrer arkose. The zircon age distribution of the Scherrer would have to vary significantly at Sierra Mojina from that at Santa Lucia or other distinct sources would have to be involved to produce the distinct assemblages found at both localities.

The gneissic basement block observed north of Moris, Chihuahua is cut by a granite dated by U-Pb in zircons at 1.44 Ga (see appendix). An age for the host gneiss has yet to be determined, but it is clearly older than 1.44 Ga. It appears very different than what has been observed in the Granite Rhyolite Province and the next oldest province known regionally is the Mazatzal.

Grenville age basement

The 1.2 to 1.0 Ga Grenville Belt continues from Eastern Canada down the Appalachians until being offset in the Mississippi Valley area and Ouachita Mountains. The offset brings the Grenville age rocks west where it continues southwest across Texas (Karlstrom and others, 1987) where it crops out in the central Texas Llano Uplift (Slagstad and others, 2009). A second offset occurs in southwest Texas where it is shifted north-northwest. In this area its distribution becomes more difficult to determine because of the extensive cover resulting in a greater spread of distribution models. Two dated occurrences of Grenville age rocks are known in Chihuahua, at Sierra Cuervo and Sierra Carrizalillo (Handschy and Dyer, 1987). As noted above, a significant population of Grenville age zircons come from the Lower Cretaceous Las Vigas Formation at Sierra Mojina.

A small block of Grenville age gneiss (1018 Ma), the Novillo Gneiss, has been documented (Ortega-Gutiérrez and others, 1995) within probable Ouachita age Granjeno Schist (250 Ma) near Ciudad Victoria. The outcrop of Novillo Gneiss is proposed to be a part of a segment of Grenville age crust, the Oaxaquia (Ortega-Gutiérrez and others, 1995). The Granjeno schist contains detrital zircons from the Grenville and the Granite-Rhyolite Terrane with some as young as Devonian and old as Late Archean (Barboza-Gudiño, and others, 2011).

Caborca

The Caborca Terrane consists of mostly of Mojave and Yavapai (1.7-1.8 Ga) age basement cut by 1.4 Ga plutons and Permian stocks (see Iriondo and others, 2004; Iriondo and Premo, 2010). A distinctive characteristic that distinguishes it from the main southern North American craton stratigraphy in southeastern Arizona and northeastern Sonora is the presence of late Neoproterozoic carbonates directly on the basement and multiple quartzite units occurring in both the Neoproterozoic section and the early Cambrian carbonate section (Farmer and others, 2005), whereas the basal supracrustal strata of the North American craton in northeastern Sonora, southeastern Arizona and southwestern New Mexico consists of a middle Cambrian through Ordovician quartzite to sandstone (Middleton, 1989).

PAN AFRICAN CRUST?

Pan African crust is only reported in the eastern Caribbean and Florida region of North America (Schlager and others, 1984) but zircons from this crust are found throughout northern Mexico (Lopez-Infanzon and others, 2001; Gray and Lawton, 2008).

As noted above, Pan African zircons are found in the Las Vigas Formation at Sierra Santa Lucia and Sierra Mojina. Both of these populations may be derived from the underlying Permian Scherrer Formation but they could be derived from some previously undetected Pan African crust in the region as discussed below.

OUACHITA (COAHUILA) BELT PALEOZOIC CRUST

Paleozoic crust resulting from the Ouachita age collision of North American (Laurentian) with South America (Gondwana) appears to underlie much of central Mexico from south of Chihuahua City to north of San Luis Potosi (Fig. 2.1). Nuevo Delicias, Coahuila (McKee and others1988), Santa Maria del Oro, Durango (Lopez, 1988) and San Lucas, Durango (Iriondo and others, 2003) have all been accepted Paleozoic ages and have been reviewed in the field. Also observed in the field are similar metamorphosed outcrops at Cerro Peñuelo, Coahuila and Pico de Teyra, Zacatecas, that have been variously interpreted as Paleozoic to Late Cretaceous stratigraphic ages (Anderson and others, 2005b).

The largest area of Paleozoic strata occurs in outcrops in the Nuevo Delicias, Coahuila area in central part of the Coahuila Platform. It is characterized by a northeast-trending fold and metamorphic fabric (McKee and others, 1988).

South of the Coahuila Platform and Mexican Basin, outcrops at Pico de Teyra on the south side of the San Julian Uplift in northern Zacatecas (Fig. 2.1) were originally labeled as the Paleozoic Taray Formation (Cordoba, 1964) but more recently have been classified as Upper Triassic and Jurassic (Anderson and others, 2005b). The Taray Formation contains a mudstone matrix containing clasts from sand to boulders overprinted with a greenschist metamorphic event and is very similar to parts of the Delicias of the Coahuila Platform. The unit was classified a mélange by Anderson and others (2005b). The Paleozoic fossils observed occur only in clasts. Detrital zircons only constrain the age between the Lower Permian (270 Ma, the youngest detrital zircon age, Diaz-Salgado and others, 2003) and the overlying Mid-Jurassic Caopas Formation (158 Ma Jones and others, 1995). A new date of 171 Ma (Sample JLSR-1, this study discussed below and Appendix A) on a Nazas tuff 75 km northwest of Sierra San Julian (Pico de Teyra) at Sierra Ramirez, Durango may further constrain the age between 270 and 171 Ma. Although Anderson and others (2005b) chose to assign the Taray strata to the Upper Triassic to Lower Jurassic, the lack of age constraints between 270 Ma and the overlying Jurassic Nazas, and the presence of an east northeast metamorphic fabric (Anderson and others, 2005b) suggests its age is most consistent with the Late Paleozoic Ouachita Orogenic strata.

A number of Paleozoic schist basement occurrences are distributed in a 450 km long north-northwest-trending belt from 37 km east of Durango City to 80 km northwest of Parral (Fig. 2.1). Dates include 326 Ma (Mississippian) at Santa Maria del Oro, Durango (Lopez-Infanzon, 1988) and 251 Ma (Permian) at San Lucas, Durango (Iriondo and others, 2003).

The known eastern limits of Permo-Triassic metamorphism of mostly Paleozoic crust include the northeastern-most Mexican outcrop at Sierra del Carmen, Coahuila just southeast of Big Bend National Park along the Texas-Mexican border. The southeastern-most outcrops of Paleozoic strata with Ouachita age metamorphism is the Granjeno schist west of Ciudad Victoria, Tamaulipas (Barboza-Gudiño and others, 2011).

NEW DATA ON THE BASEMENT OF NORTHWESTERN MEXICO

New data on the Mexican basement includes newly-discovered outcrops, a drill intercept of gray mica schist near Ciudad Durango, U-Pb dates on both rock outcrop and detrital zircon data on clastic units of various ages. Two previously undescribed occurrences of interpreted Paleozoic basement include an outcrop of greenschist grade mica schist cropping out on the north side of Cerro Peñuelo in the southeasternmost corner of Coahuila and a recent discovery of gray weakly graphitic schist in a mineral exploration hole 35km east northeast of Durango, Durango.

Cerro Peñuelo, Coahuila

On the north side of Cerro Peñuelo in southeasternmost Coahuila (Fig. 2.1), a new occurrence here interpreted as metamorphosed Paleozoic clastic rocks. They crop out as coarse white mica-rich sandstone, conglomerate and shale with a variable north dipping east northeast foliation well developed within the mica. The low grade metamorphism appears to be lower green schist. The outcrops look very similar to facies of the Taray Formation (Pico de Teyra) 140km to the west in northern Zacatecas (Anderson and others,.2005b). Boulder beds such as at Pico de Teyra were not observed at Cerro Peñuelo during this study, but other facies and lower greenschist metamorphism are very similar to the Taray strata. The east-northeast foliation and cleavage fabric observed are essentially the same at both localities. No recognition of a possible Paleozoic age for Peñuelo strata was encountered in the literature, and it appears that previous investigators if they observed it (e.g. Padilla y Sanchez, 1985) may have considered it contact metamorphosed sedimentary strata resulting from the nearby Peñuelo stock. The outcrop is approximately 700m from the stock margin where the contact metamorphism, while poorly exposed, appears to be on the order of tens of meters at most. The structural fabric of this outcrop trends east northeast, very similar to the Taray Formation. Lacking confirmation from radiometric dating, a correlation with an Ouachita orogenic event appears most consistent with the limited data.

Salamandra (Cerro Pilar), Durango

The most recent basement discovery is in a shallow mineral exploration drill hole 35km east northeast of Durango City on the west flank of Cerro Piojo (Salamandra Figure 2.1), an Eocene vent west of the Oligocene tuffs that make up Cerro Pilar. In exploration drill hole SA-18 (567,380E 2,670,850N UTM NAD 27 Zone 13R, drilled southwest at -50°) after collaring in alluvium Cenomanian-Turonian Indidura was intersected at 2.75 m and followed by the contact between the Indidura and Nazas at 140 m down hole (100 m below the surface). Within the Indidura section numerous debris flows of limestone clast in a mud matrix were encountered. The limestone fragments displayed sparse unidentifiable coarse fossil fragments. Numerous outcrops of fragmental debris including limestone and schist fragments originally mapped as breccia pipes are now interpreted as debris flows in channels. One prior clue was the absence of the breccias in drill holes. From 140 m to 351 m classic Jurassic Nazas dacitic flows and volcaniclastic rocks were encountered. This correlation is based on stratigraphic position and lithologic correlation with known Jurassic outcrops southwest of Gomez Palacio, Durango (Lawton and Molina-Garza, 2014) and the dacitic tuff in an inverted basement block at Sierra Ramirez, Durango, sample JL-SR-1, dated in this study at 171.5±2.8Ma (see Appendix). At 351 m (266m below the surface) the drill hole entered a graphitic micaceous schist cut by abundant white metamorphic quartz veins and scattered tectonic breccias that continued down the hole until 597 m depth. This schist is considered to have a Permo-Triassic age from its strong similarities with the dated schist (251Ma, Mungia and others, 1998; Iriondo, 2001) just north of San Lucas, Durango, 73km north of this new basement occurrence.

San Lucas del Ocampo, Durango

Although the location and ages of the Paleozoic schist at San Lucas del Ocampo are not new and are discussed above, the structural fabric of the schist has not been previously documented. The azimuth of the foliation averages 070° and the dips measured ranged from 10 to 30° south. These orientations of strikes are compatible with the general orientation of the Permo-Triassic metamorphosed Paleozoic age rocks found from Taray, Zacatecas to Nuevo Delicias,Coahuila.

Parral Terrane-Valle de Olivos

Higher grade micaceous schist not characteristic of the Ouachita metamorphism crops out northwest of Parral, Chihuahua in line with the known Paleozoic basement outcrops of Santa Maria del Oro and San Lucas, Durango (Fig. 2.1). This basement outcrop has been partially mapped (Mungia and others, 1998), but more detailed studies were not located. While it is mapped as the Parral Terrane and considered to be Paleozoic, this schist displays a north-northwest fabric and is considered to be basement older than Paleozoic because of its higher grade of metamorphism and contrasting fabric with known and interpreted occurrences.. It has been poorly studied and clearly needs more investigation particularly with radiometric dating.

REINTERPRETATION OF ISOTOPE DATA

The earliest isotopic studies focused on the interpretation of the northern Mexico basement were Pb isotopic studies by Silver and Anderson (1974). A discontinuity in the data in the region around Chanate (Fig. 2.1) in northwestern Sonora was interpreted as evidence of a major left lateral early to middle Mesozoic disruption cutting across the Mexican craton, the Mojave-Sonora Megashear. Despite the documented presence of an important Jurassic and Lower Cretaceous basin crossing the path of the proposed transform fault, this model became a major ruling theory of later models of the basement.

Broader studies of the isotopic signatures believed to reflect the underlying crust of Chihuahua and parts of Sonora and Texas include the studies of James and Henry (1993) and Housh and McDowell (2005). Structural mapping that forms the basis of this study, along with two detrital zircon studies reflecting basement sources, did not correspond with the provinces based on the combination Nd, Pb and Sr as interpreted by Housh and McDowell (2005). Based on published data sets of Cretaceous and Cenozoic magmatic activity for the Great Basin (Farmer and DePolo, 1983), and Southern Arizona (Farmer and DePalo, 1984), they concluded ε_{Nd} appears to be the best isotopic tool for deciphering age patterns of buried crust. Contouring the ε_{Nd} data of Housh and McDowell (2005) alone appears to confirm this conclusion (Fig. 2.4). The new contoured fields (Fig. 2.5) where ε_{Nd} was less than -4 appears to correspond to the Mazatzal Province and consistent with Mazatzal data from Farmer and DePalo (1984). Samples with ε_{Nd} ranging from -2 to -4 corresponds to a region of north central Chihuahua that may be underlain by Granite-Rhyolite Province based on the detrital zircon study at Cinco de Mayo and Sierra Mojina. The belt of ε_{Nd} values between -2 and 0 ties with what is assumed to be the Grenville Province rocks and corresponds with Grenville age outcrops at Cuervo and Carrizalillo, Chihuahua. The ε_{Nd} values of 0 to 2 represent an unknown region but based on the presence of Pan-African detrital zircons in the Sierra Mojina sample, it may be the basement age of this region. South of this area isotopic data is widely dispersed, but based on outcrops it is assumed to be Paleozoic crust of Ouachita age with some fragmental blocks of Grenville age basement.

Correlation of Regional Aeromagnetic Signature and Basement

There are many versions of aeromagnetic maps of Mexico, with most of the data coming from Petroleros Mexicanos (PEMEX) and Servicio Geologico Mexicano (SGM) and having various processing formats: total magnetic intensity (TMI), reduced to pole (RTP) and various derivative maps. The most accessible map is a USGS compilation of all of North America (Brumstein ed., 2002). Many versions of the magnetic map of Mexico have been analyzed for fabric patterns that reflect variations in the crust, structural offsets of the basement fabric, structural block rotations and magmatic complexes. Some variations of processing accentuate features such as the buried edge of the craton while others accentuate features such as the Tertiary volcanic cover. The version presented here is interpreted from Brumstein's (2002) map (Fig. 2.6). The technique used simply plots lines along alignments of highs and lows. Some of the broader features appear to represent simple expanses of uniform basement. The very noisy appearance of much of the magnetic data of western Chihuahua, southwestern Durango, eastern Sonora and the west coast of Mexico has been recognized in the field as constantly reversing of polarity of stacked volcanic tuffs and flows within irregular topography. Figure 2.7 shows the correspondence between Sierra Madre Occidental volcanic field and the noisy aeromagnetic data produced by the deeply incised extensive Sierra Madre Occidental Volcanic Province.

Figure 2.8 is a map highlighting the magnetic ridges as solid lines and the magnetic troughs as dashed lines. Most anomalous features on the west coast correspond to various elements of the Sonora-Sinaloa batholith. The basement fabric still appears to be traceable through the higher frequency magnetic noise from the volcanic cover. The boundary between the marginal basin and the Precambrian and Paleozoic core of Mexico is based in part on north-northwest-trending magnetic fabric that aids in connecting the

Cananea Papago-Mazatzal crust boundary with the inverted basement core block from Parral to north of the City of Guanajuato. This inverted basement block separates the Permo-Triassic metamorphic age crust from the marginal basin.

It is commonly argued that aeromagnetic basement fabric is not visible through volcanic cover (Aiken and others, 1997). Many years of experience with aeromagnetic data including data acquisition at different elevations and upward continued data for the purpose of recognizing deeper features would argue otherwise. The simplest approach to present this argument is to plot the magnetic lineaments extracted from the data (Fig. 2.9) over the volcanic cover where it can be noted that most of these linear trends particularly in Sonora and Chihuahua cross the boundary between volcanic cover and non-covered areas.

The magnetic fabrics interpreted in northern Chihuahua follow similar patterns to the reinterpreted value fields of Housh and McDowell's ε_{Nd} data (Fig. 2.10). This similarity strengthens the proposed model for northern Chihuahua crust.

BASEMENT DISCUSSION

The basement of Mexico is known from limited outcrops and oil and mineral exploration drill holes. From this limited knowledge base some extrapolation has been done from isotopic, magnetic and gravity geophysical studies with mixed results. Most studies of the aeromagnetic data for Mexico consist of modeling of the data along cross sections (Aiken and others, 1997). Their conclusion was that the volcanic field effectively hides any magnetic signature of the underlying basement. Experience of working with aeromagnetic data in volcanic fields for 40 years has shown that the majority of magnetic anomalies derived directly from the volcanic rocks produces high frequency anomalies related to the constant magnetic reversals of alternating polarity and their exposure as stacked reversely polarized beds. Larger amplitude magnetic features cross between volcanic covered and non-covered areas, and often correspond to major tectonic features when the basement is well enough exposed.

The interpretation of magnetic data by Handschy and others (1987) suggests that after the outcrops of the Big Bend area of west Texas the boundary between the Paleozoic Ouachita basement and the Grenville to the north turns south into Mexico along the Chihuahua-Coahuila border. The western edge of the Grenville Province was interpreted to be reflected in a magnetic ridge underlying the Big Bend area of west Texas. An apparent south-trending branch of the anomaly into Mexico has been interpreted as indicating that the Grenville Province turns south into Mexico (Handschy and others, 1987). This is inconsistent with isotopic studies (James and Henry, 1993) and the evidence of basement weakness where the volcanism sweeps the farthest to the east-northeast into west Texas. A second weaker branch off of the main magnetic anomaly that continues southwest of the main anomaly appears to reflect the west-southwest interpretation. A reinterpretation of isotopic data (Housh and McDowell, 2005) focusing on ε_{Nd} produces an isotopic distribution more consistent with the structural and magnetic data presented here

The distribution of the Mezcalera overthrust is interpreted as reflecting the distribution of Paleozoic crust of north central Mexico in the states of Coahuila, southern Chihuahua, northern Zacatecas, northeastern Durango and northern San Luis Potosi. The less mature Paleozoic crust represents shallower less buoyant crust. The marine strata of the marginal basin appear to have thrust over the less buoyant Paleozoic crust more easily than over the Grenville and older crust. The overthrust has been mapped in this study both in detailed and reconnaissance mapping for 760km from 60km northwest of Parral to 140km southeast of Zacatecas (Fig. 2.11).

The proposed theory of a Grenville age Oaxaquia basement underlying the north central highlands of Mexico (Ortega-Gutierrez and others, 1995) is somewhat problematic with the widespread greenschist metamorphic basement encasing these older granulites. The required shortening to produce the observed metamorphosed and deformed Paleozoic crust is inconsistent the presence of an older more mature crust underlying it unless it was highly fragmented or extended before the Ouachita Orogeny. One interpretation worth consideration is the possibility that the Grenville age granulite outcrops west of Ciudad Victoria align with the south end of the Cenomanian Mezcalera overthrust to define the south edge of the Ouachita age crust where it was thrust onto the Oaxaquia Grenville age crust of southern Mexico. Fragments of extended crust produced during the rifting of Rodinia that formed the basin of the Iapetus ocean may account for the Grenville age xenoliths brought up in young vents. The filling of the Iapetus basin during the Paleozoic produced the sediments encasing these fragments that were then metamorphosed during the Appalachian-Ouachita Orogeny resulting from closure of the Iapetus.

During this study two new occurrences of basement were documented: one an outcrop several hundred meters long on the north side of Cerro Peñuelo in southeasternmost Coahuila and one in a mineral exploration drill hole 37 km east of Durango City. None of the new occurrences have been dated yet but from the schistose character and locations both are assumed to be Paleozoic schist of the Ouachita Tectonic belt. The Peñuelo outcrop is very similar to mudstone, sandstone and conglomerate facies of the Taray Formation 140km to the west of Peñuelo. The Taray Formation contains abundant clasts, some fossiliferous, of Paleozoic strata as reported by Anderson and others, 2005. The youngest zircon reported in detrital zircon studies (Diaz and others, 2003) is 270Ma (Permian) that bounds deposition between the Early Permian and the overlying Nazas Formation (Early through Middle Jurassic). There is no firm evidence for selecting any specific age between the 270Ma zircon and the overlying Nazas. The abundant Permo-Triassic magmatism in the region could reasonably expected to be reflected in younger strata. The lack of a compressive tectonic event between the Ouachita Orogeny and the Mid-Cretaceous Mezcalera thrust suggests that the low grade greenschist metamorphism is a result of the Ouachita Orogeny, not a later Mesozoic orogeny.

The Caopas Formation at the base of the Nazas has been interpreted (Jones and others, 1995) as being a schistose volcanic rock and therefore used to define a tectonic event. This texture has been observed in this study in northwestern Sonora as well as the Caopas formation in this study and has been interpreted at both localities as a thick waterlain pumice tuff that if deposited subaerially would have formed a welded tuff. The original glass appears to have been altered rapidly to clay in the marine environment and the pumice flattened to a eutaxitic texture. This flattened pumice and argillized glass produces a laminar sheeted texture, that is often interpreted as schist, but with no evidence of shear fabric, such as a lineation.

The Nazas block at Sierra Ramirez and the Nazas and Taray Formation in Sierra San Julian are both interpreted as inverted basement blocks that were thrust south southeastward up out of the Mexican Basin during inversion of the transvers portion of the basin starting in the Cenomanian..

Because the Las Vigas Formation at Sierra Santa Lucia and Sierra Mojina would have been separated from known sources of zircons dated at these localities by both the Carrizal and Chihuahua Basins, the zircons would most likely have been derived from the Casas Grandes platform to the west.

Most rifting events of the North American craton discussed in the literature are proposed Late Neoproterozoic rifting of Rodinia into North America and variously into Antarctica, Australia, Siberia and China, (see Iriondo and Premo, 2011 for a discussion). These events are too early to be the rifting that would have cut the Paleozoic rocks of the Ouachita Orogeny that crop out in the state of Durango.

The opening of the Gulf of Mexico and important intracratonic basins in the Mid-Jurassic was another major event affecting the Mexican crust. Many authors (for example Haenggi and Muehlberger, 2005) relate the opening of the intracratonic basins to the opening of the Gulf of Mexico.

Integrating the extensional regime of the Jurassic and the accretion of the Guerrero Terrane requires a complex model utilizing 3 different subduction zones (Dickinson and Lawton, 2001) with slab rollback on the east side of the Mezcalera Ocean providing the extensional mechanism. The model proposed here achieves the same results with a much simpler model of the Jurassic Nazas Arc sweeping out past the marginal basin to the Alisitos Arc position by steepening of the subducting Farallon plate and producing the proposed extensional regime by this plate rollback.

The styles of late Cretaceous and Paleogene deformation have proven to be the most useful features for helping to delineate the intracratonic basins. Thrust faults rising out-of-the-basins during basin inversion clearly define the structural margins while facies shift laterally as basins fill and sea level changes through time. The numerous blocks of basement surrounded by Upper Jurassic deep marine strata suggest a Jurassic rifted margin that then started accumulating strata along the rifted margin producing a marginal basin. The only well documented event placing the Caborca against this marginal basin is the Cenomanian shortening that thrust the Caborca basement up over the Upper Jurassic and Lower Cretaceous strata at Cucurpe (Maul and others, 2011), Creston, and Sahuaripa

(Pubellier and others, 1995). Coeval thrusting of the Mezcalera Overthrust on top of the Ouachita Crustal Province with its supracrustal Jurassic Nazas volcanic strata, Zuloaga platform carbonates and Lower Cretaceous platform carbonates further document the timing and extent of this shortening event. Numerous fossil determinations date the Mezcalera strata as Upper Jurassic and Lower Cretaceous, the same as the marginal basin (Eguiluz de Antunano and Campa-Urango, 1982; Mungia Rojas and others 1998).

Further work needed to test these ideas includes more radiometric dating at localities such as Peñuelo, Valle de Olivos, Salamandra (pending), and the host gneiss at Moris. Because of obvious resetting of K-Ar dates from PEMEX cores or outcropping stocks that have K-Ar dates inconsistent with their geology, a valuable project would be to re-date them with U-Pb if possible.

BASEMENT CONCLUSIONS

New radiometric ages (though limited in number), regional consistency of an east northeast to north northeast metamorphic fabric and the north to south limits of the Mezcalera overthrust suggests that the majority of central Mexico is underlain by Paleozoic Ouachita Orogeny greenschist grade metamorphic sedimentary and volcanic rocks (Fig. 2.10). The dated or otherwise presumed outcrops of Grenville age granulite facies in north central Mexico do not appear to have been a continuous high grade metamorphic crust but fragmental debris from rifting of Grenville age crust. This is indicated by the significant shortening with metamorphism displayed by the exposed Paleozoic rocks encasing the Grenville age rocks.

Paleozoic crustal occurrences are known at Santa Maria del Oro and San Lucas, Durango; Sierra del Carmen and Delicias, Coahuila; and Pico de Teyra, Zacatecas. New occurrences are now known at Peñuelo, Coahuila, and at Salamandra (Cerro Pilar), Durango, along a proposed inverted basement uplift of Ouachita age metamorphism of a Paleozoic age protolith help strengthen the model of Paleozoic crust for the highlands of central Mexico. A new structural interpretation of the distribution of Mezcalera thrust makes use of the distribution of the overthrust to delimit the possible distribution of younger thinner lighter less buoyant Paleozoic crust that was more subject to be overridden by adjacent marginal basin strata during shortening. Based on field observations, the overthrust runs from north of Parral, Chihuahua, to south of Zacatecas, Zacatecas (Fig. 2.11).

A new interpretation of the data of Housh and McDowell (2005) is based on patterns of populations of ranges of values of the ε_{Nd} data alone. This produces a pattern modified from their combined ε_{Nd} Sr and Pb isotope data they presented (Fig. 2.5). Based on the work of Farmer and DePalo (1983, 1984) in the southwestern U.S.A. it is believed that the ε_{Nd} is more representative of the basement age. This reinterpretation produces a pattern closer to the aeromagnetic interpretations and geology.

A new interpretation of a total magnetic intensity aeromagnetic map of Mexico is based on delineating anomalous troughs and ridges in the magnetic data. Despite the high frequency noise produced by polarity reversals from the large Sierra Madre Occidental volcanic field, magnetic linear features interpreted to reflect basement features can be followed from outside of the volcanic field through the volcanic field (Fig. 2.9). Magnetic patterns in Chihuahua appear to correlate with the revised interpretation of published ε_{Nd} (Housh and McDowell, 2005). A long linear south southeast-trending magnetic pattern from Cananea, Sonora, through southwestern Chihuahua and Durango corresponds spatially to the Durango Inverted Basement block between the western or Mezcalera marginal basin (defined in the next chapter), the North American craton and the Permo-Triassic metamorphic crust of central Mexico. Structural inversion often produces a rotation of the involved basement. The associated rotated magnetic field that can produce significant magnetic anomalies as observed on a smaller scale at Sierra Santa Lucia.

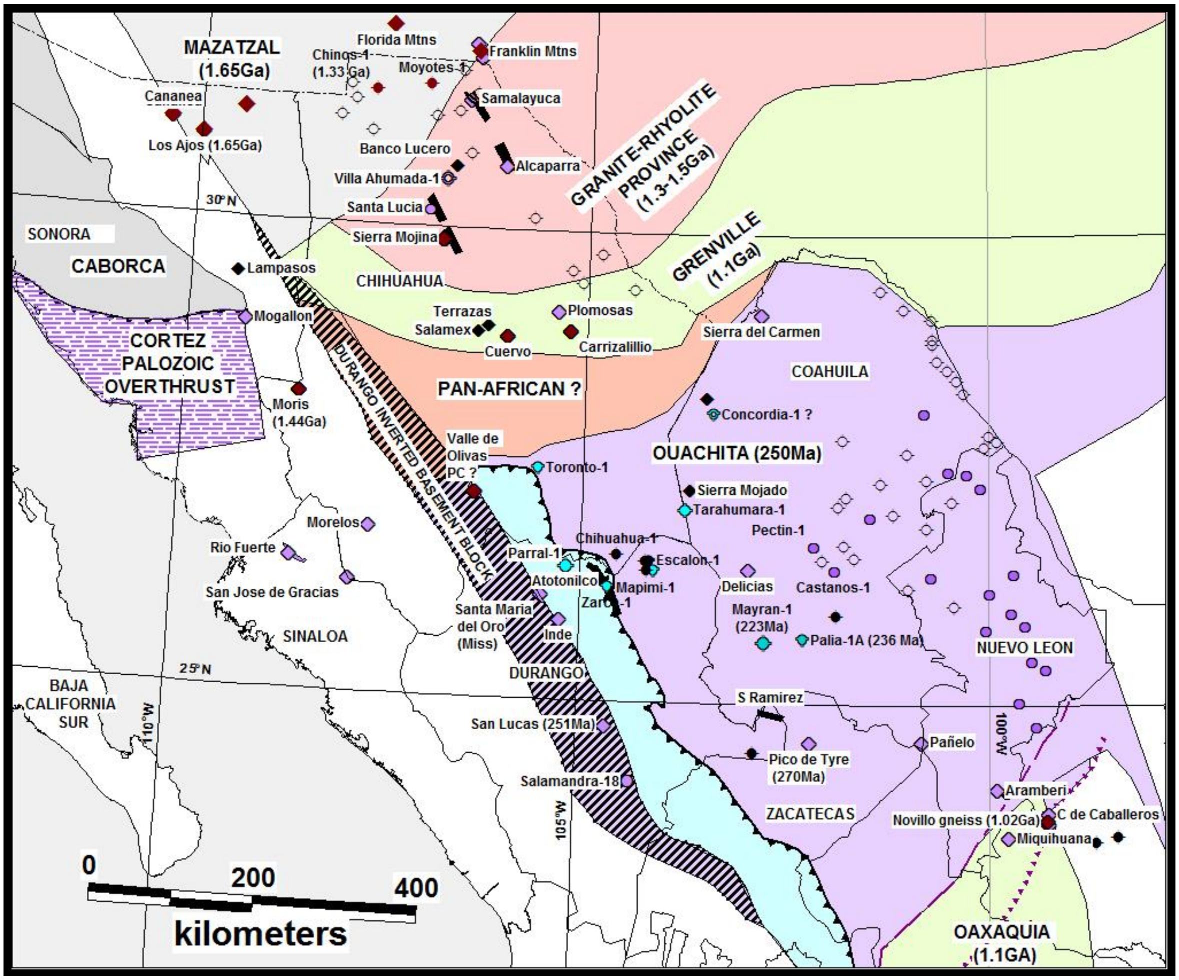


Figure 2.1 Tectonic map of northern Mexico showing Pre-Mesozoic basement outcrops and the interpreted fields of each basement type.

Bases of the interpreted basement fields are presented in this chapter. Shown here are the initial data points to be expanded upon. The Tuscan red diamonds represent outcrops of Precambrian basement except as Sierra Mojina where schist of volcanic protolith dominate Lower Cretaceous La Vigas Formation and is interpreted as sourced nearby. The purple diamonds represent Paleozoic outcrops. All purple diamonds within the purple Ouachita field, those on Oaxaquia and the two outcrops at Rio Fuerte and San Jose de Gracias are deformed metamorphosed Paleozoic rocks. Those on Precambrian basement to the north are undeformed but often altered supracrustal strata. The Santa Lucia and Sierra Mojina localities represent the mostly Precambrian detrital zircons recovered from the Lower Cretaceous Las Vigas Formation that rests on Permian supracrustal strata. Blue localities are Nazas reported in drill holes and blue-green localities are Triassic dates.

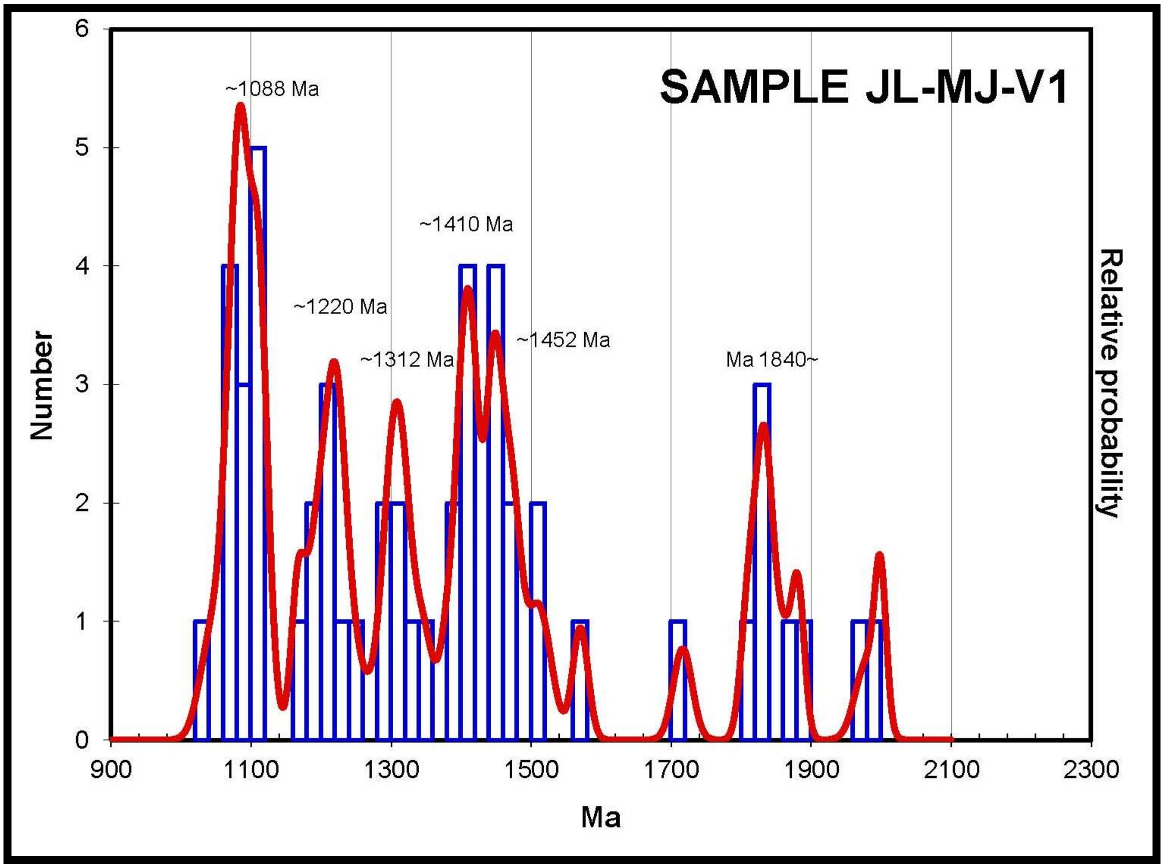


Figure 2.2 Relative probability plot of Proterozoic zircons for sample JL-MJ-V1 from Lower Cretaceous Las Vigas conglomerate at Sierra Mojina, Chihuahua.

Proterozoic detrital zircons are dominated (35/100) by Grenville (1000-1250 Ma) through (also 35/100) Granite-Rhyolite Province ages (1280-1520 Ma). Single Mazatzal or Yavapai age zircons are insignificant with (18/100) Mojave age zircons (1800-2000 Ma) dominating the Paleoproterozoic (see data in Appendix A and Supplemental Data). Four Pan African (700-900 Ma) zircons (not plotted) represent so far undocumented basement.

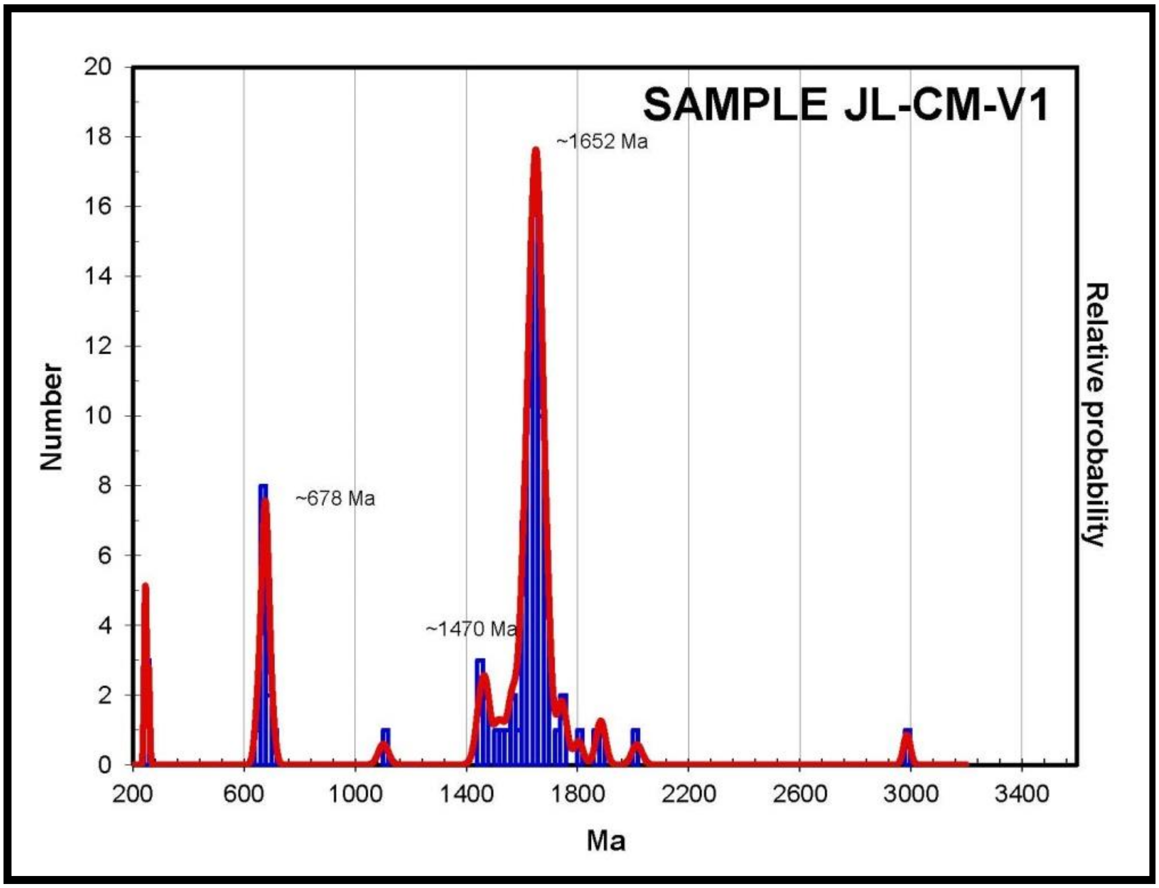


Figure 2.3 Relative probability plot for sample JL-CM-V1 from a drill hole CM10-247 on the west side of Sierra Santa Lucia, Chihuahua.

The Las Vigas at this locality is a 0.5m thick white sandstone resting between the overlying Lower Cuchillo and the underlying Permian Scherrer arkose. The most significant peak is 1652Ma (53/100 within 1600 to 1700 Ma) that represents the Proterozoic Mazatzal orogeny. The second peak (13/100zircons) at 678Ma represents the Pan-African event. To date Pan-African is not known in outcrop in this region but is proposed from the reinterpretation of ε_{Nd} data from Housh and McDowell (2005). There also are small peaks (13zircons) at 1470Ma from the Granite-Rhyolite Province and 3 Permo-Triassic zircons (see data in Appendix A and Supplemental Data). Drill hole CM10-247 is a vertical hole located at 303,158E 3,339,942N UTM NAD 27 Mexico Zone 13R.

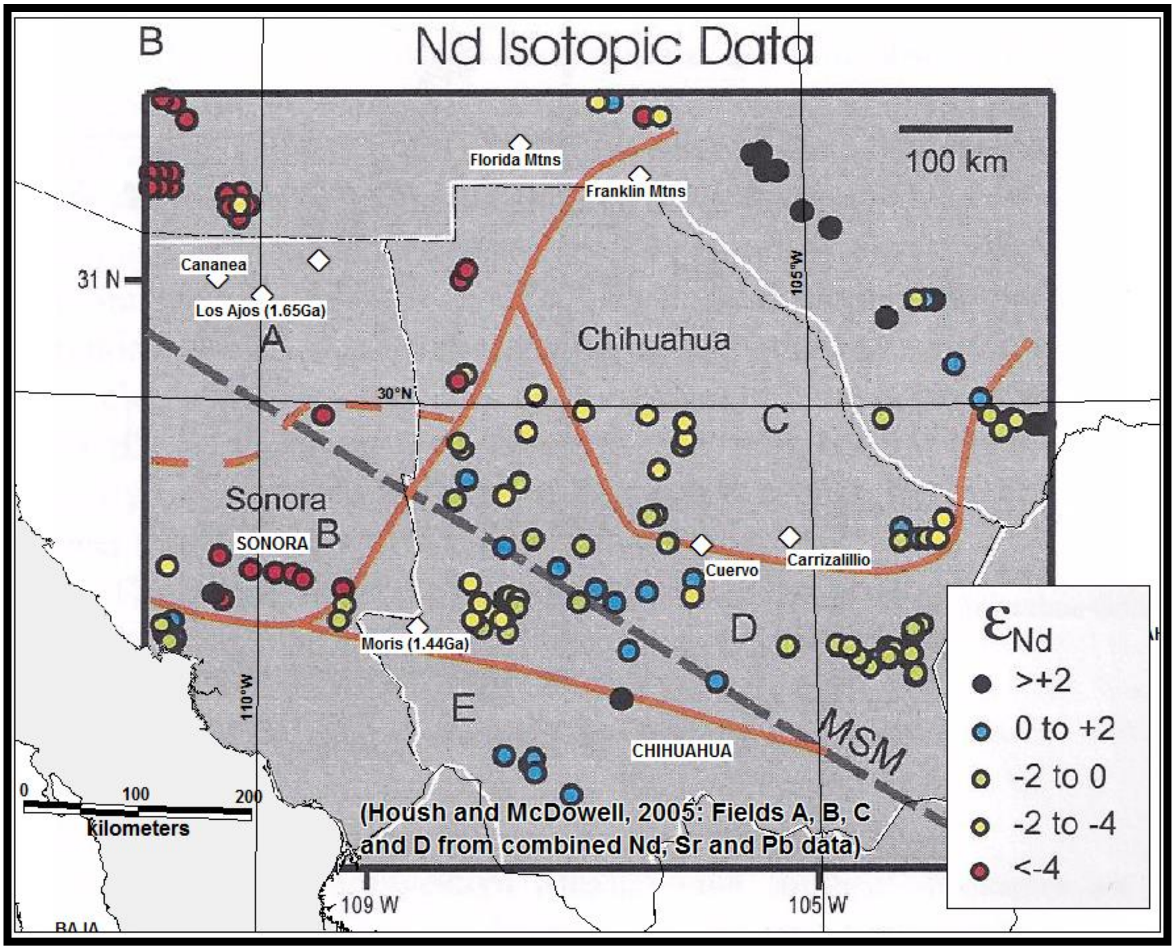


Figure 2.4 The plot of ε_{Nd} for Upper Mesozoic through mid-Tertiary igneous samples from Chihuahua and surrounding areas (Housh and McDowell, 2005).

ε_{Nd} values as shown in Legend. MSM is the trace of the Mojave-Sonora Megashear and the pale red lines are the boundaries of the fields as defined by Housh and McDowell (2005) based on their combined ε_{Nd}, and Sr and Pb isotopic data. The red diamonds are known Precambrian outcrops and the open red diamonds are detrital zircon data from this study.

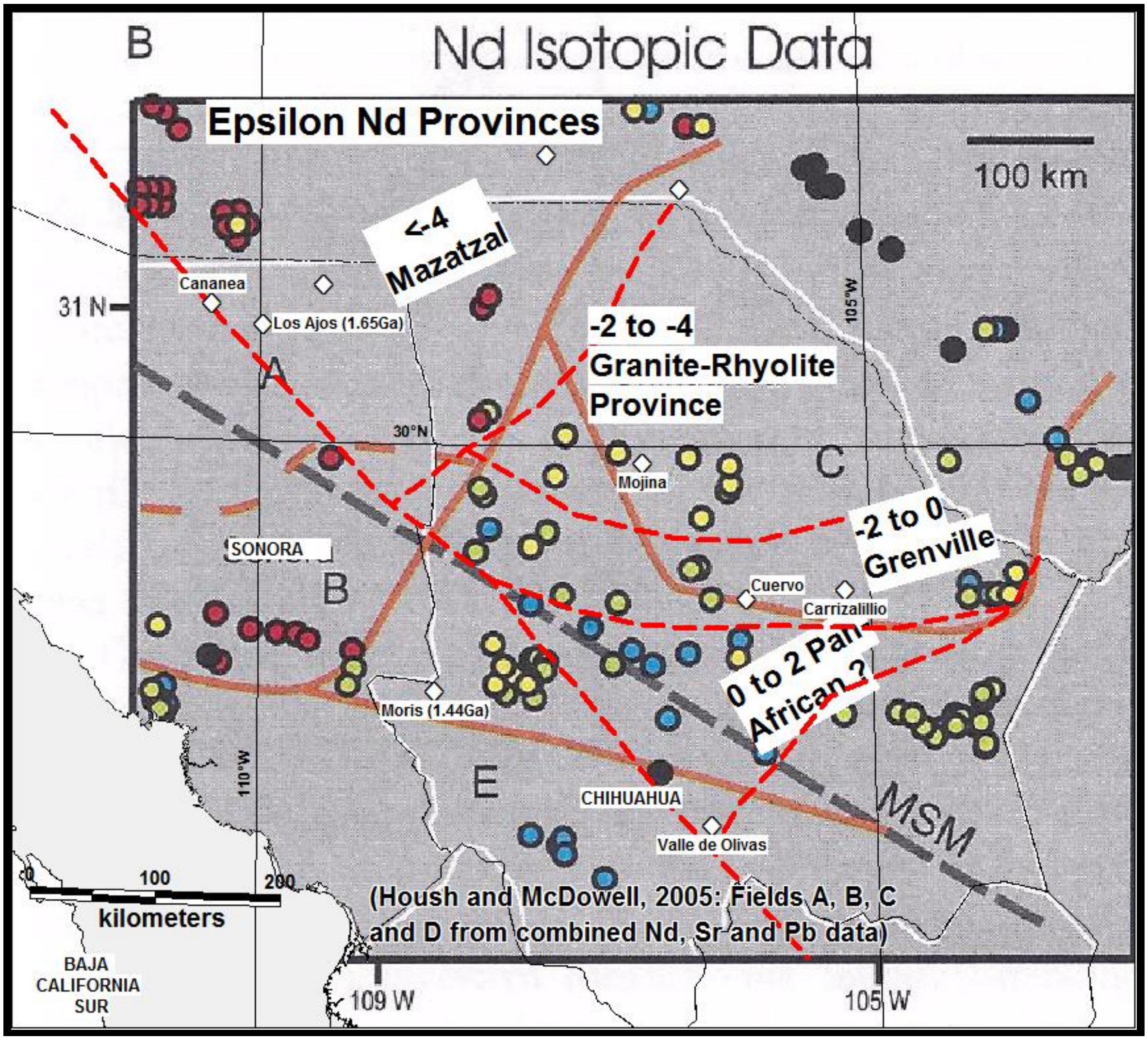
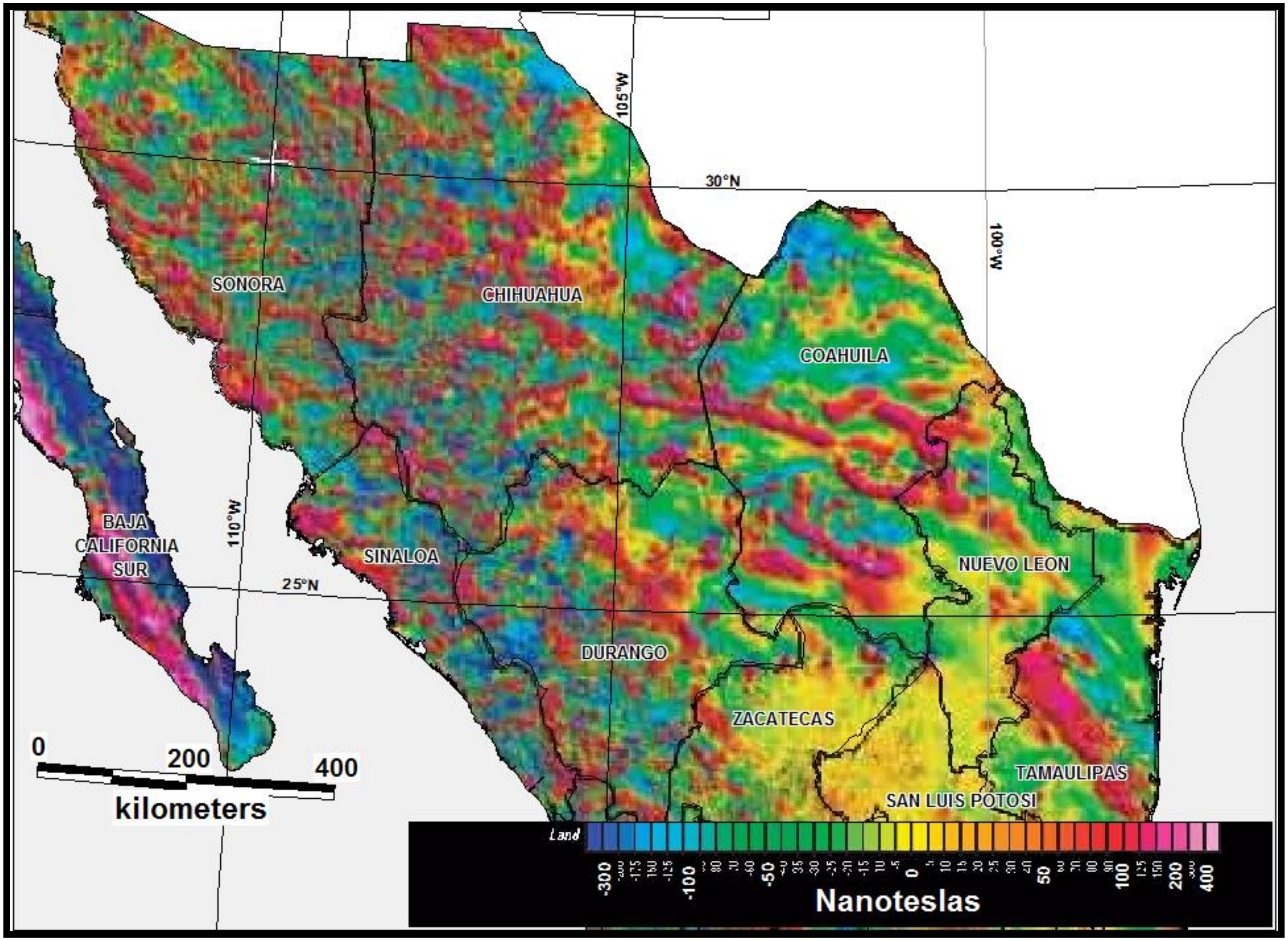


Figure 2.5 Interpreted ε_{Nd} provinces with boundaries shown as red dashed lines from the ε_{Nd} data of Housh and McDowell (2005).

Based on ε_{Nd} alone, each interpreted province contains some values outside the labeled range but peak distribution of values falls within the indicated range (<-4, 3out of 4 values; -4 to -2, 7 out of 8 values; -2to 0, 11 out of 17 values. Most variations tend to be higher values representing younger crust such as younger plutons within the older crust. Farmer and DePolo (1983, 1984) state that ε_{Nd} values better reflect crustal province boundaries. The distribution of data in the southwest was difficult to resolve into fields because of the erratic distributions of limited samples(symbols are the same as Figure 2.4).



105°W
30°N
100°W
SONORA
CHIHUAHUA
COAHUILA
BAJA
CALIFORNIA
SUR
110°W
SINALOA
25°N
NUEVO LEON
DURANGO
ZACATECAS
TAMAULIPAS
SAN LUIS POTOSI
0
200
400
kilometers
Land
-300
-100
-50
0
50
100
200
400
Nanoteslas

Figure 2.6

Figure 2.6 Mexico segment of the total magnetic intensity aeromagnetic map of North America (USGS, Brumstein ed., 2002). Pemex and SGM contributed most of the data used in the Mexico segment.

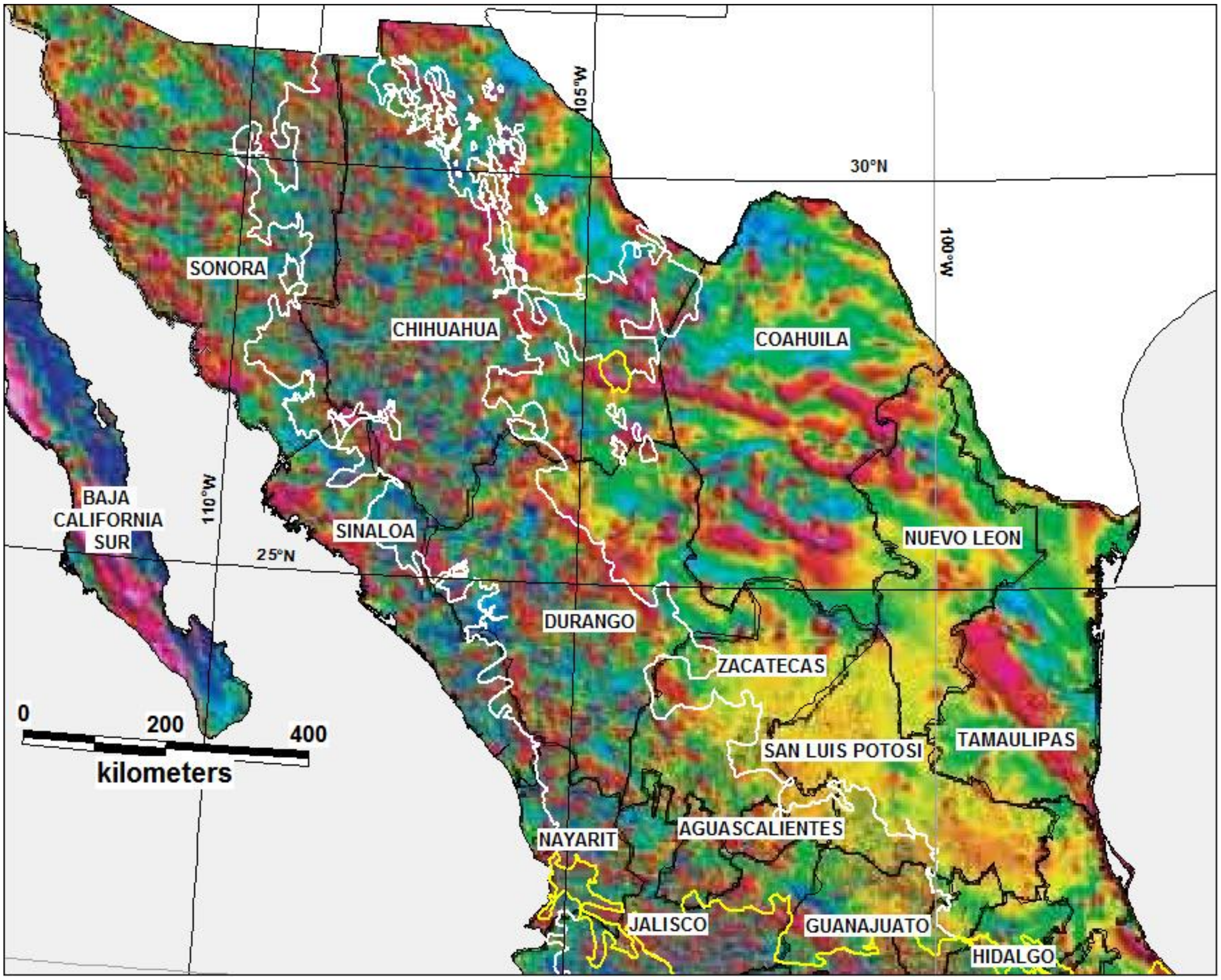


Figure 2.7 Tertiary Mexican volcanic fields plotted over the magnetic map of Mexico (Brumstein, 2002).

Outline of the Sierra Madre Occidental Volcanic field (white) and of the Trans-Mexican volcanic field (yellow) The correlation of higher frequency anomalous areas and the volcanic rocks becomes apparent. This high frequency "noise" is produced by the reversal of polarity in successive volcanic flows and tends to hide the patterns of the magnetic patterns of the underlying rocks. Stronger lower frequency anomalies do show through the volcanic noise.

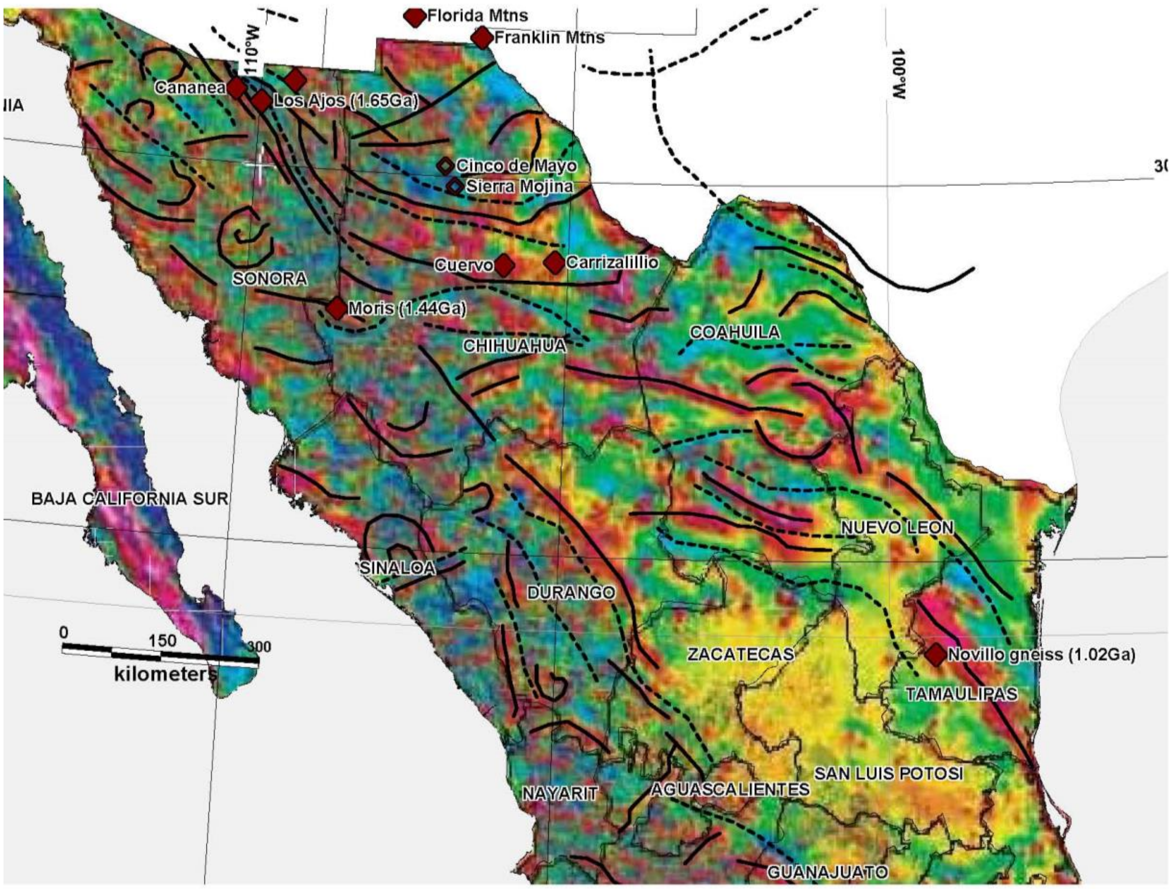
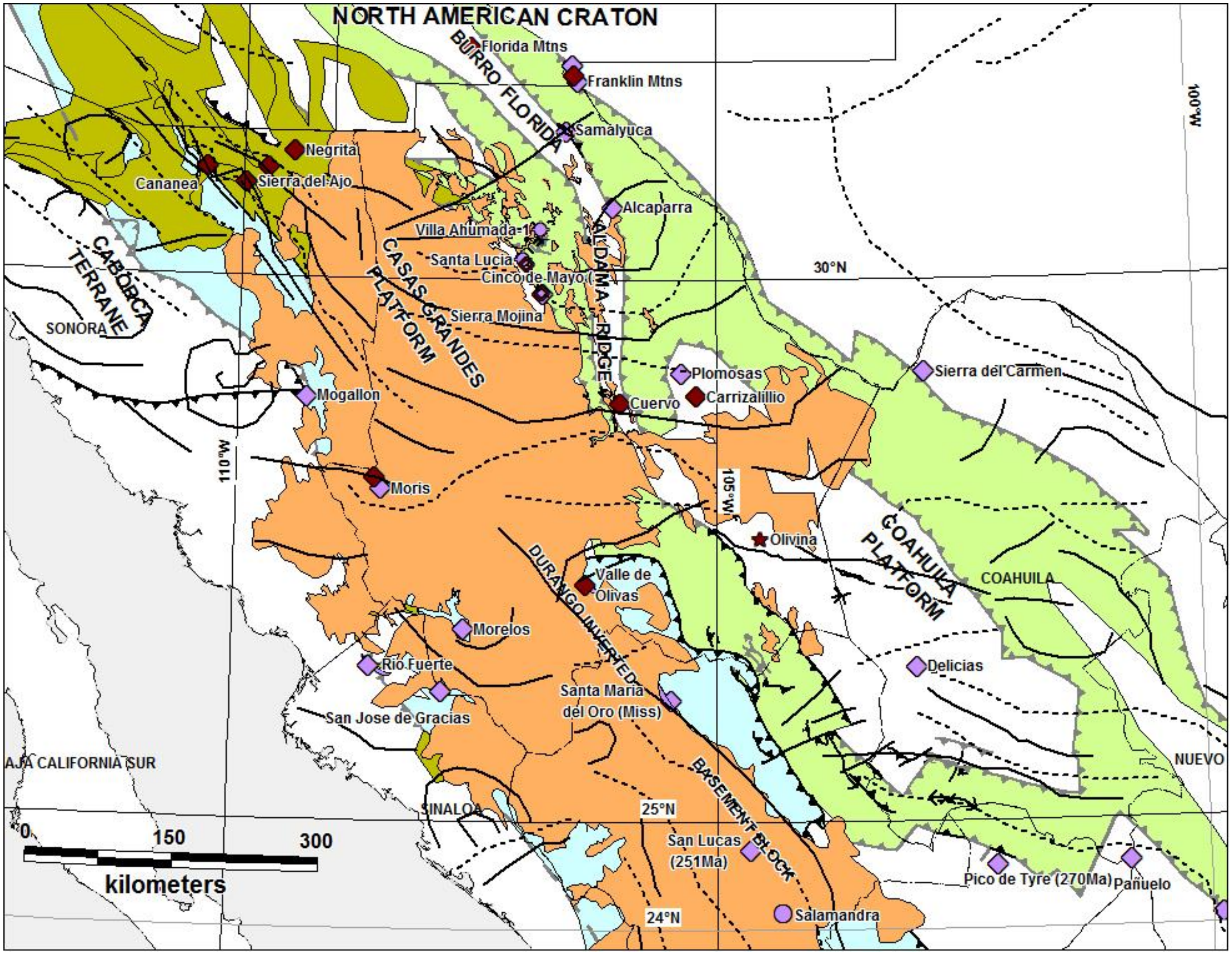


Figure 2.8 Plot of linear features of aeromagnetic data.

By tracing linear anomalies both highs (as solid lines) and lows (as dashed lines) magnetic fabrics of the basement and younger magmatic bodies can be delineated.



NORTH AMERICAN CRATON
Florida Mtns
Franklin Mtns
BURRO FLORIDA
Samalyuca
Negrita
Cananea
Sierra del Ajo
Alcaparra
Villa Ahumada-1
Santa Lucia
Cinco de Mayo
ALDAMA RIDGE
CASAS GRANDES PLATFORM
CABORCA TERRANE
SONORA
Sierra Mojina
30°N
100°W
Plomosas
Carrizalillio
Sierra del Carmen
Mogallon
Cuervo
110°W
105°W
Moris
Olivina
COAHUILA PLATFORM
COAHUILA
Valle de Olivas
DURANGO INVERTED BASEMENT BLOCK
Morelos
Rio Fuerte
Delicias
Santa Maria del Oro (Miss)
San Jose de Gracias
AJA CALIFORNIA SUR
NUEVO
SINALOA
25°N
0
150
300
kilometers
San Lucas (251Ma)
Pico de Tyre (270Ma)
Pañuelo
24°N
Salamandra

Figure 2.9

Figure 2.9 Low frequency aeromagnetic linear features from Fig. 2.8 plotted over geology illustrating the lack of relationship between volcanic rocks and most low frequency anomalies.

Boundary between Cucurpe basin and North American craton very pronounced as is the Durango inverted basement block.

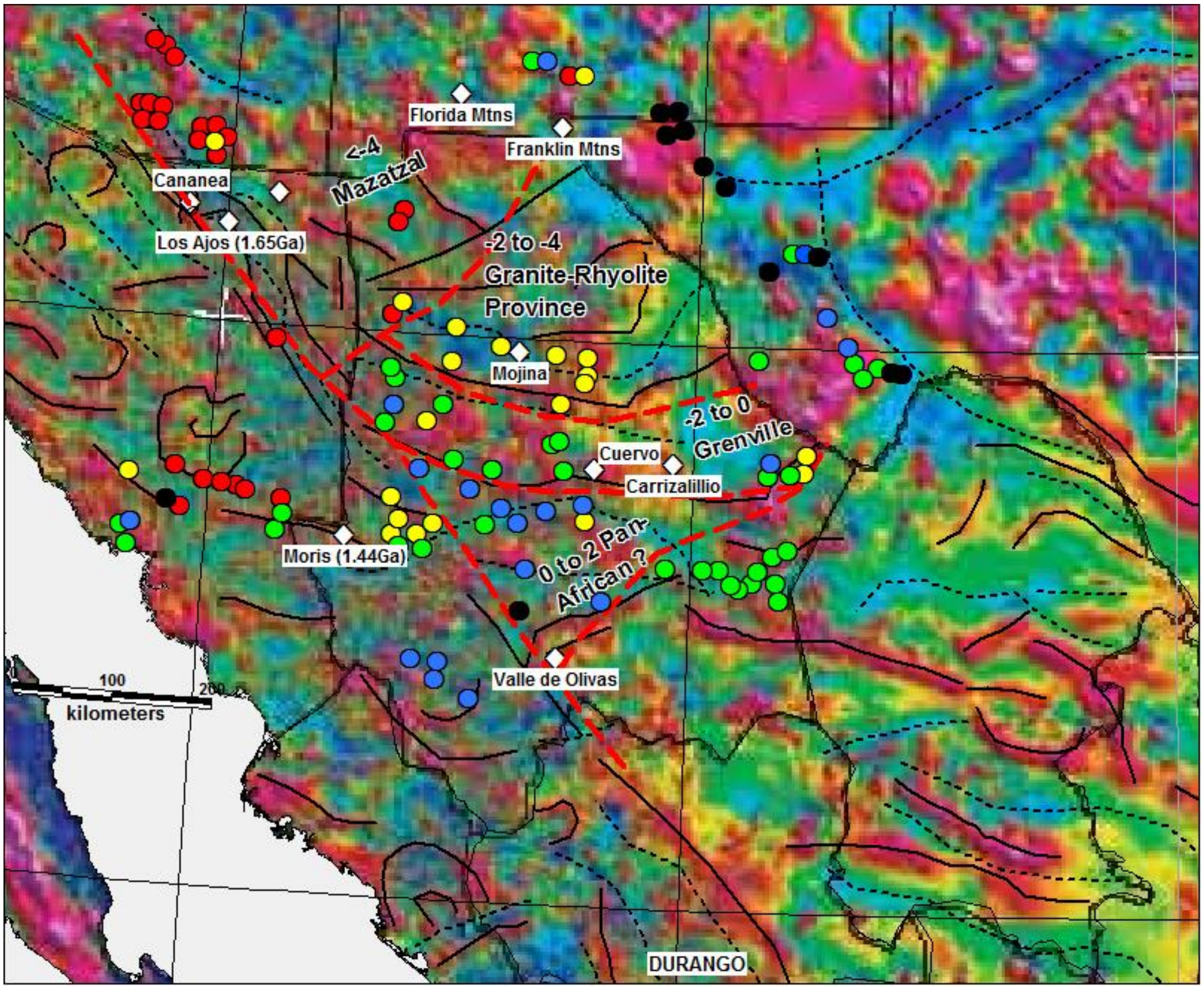


Figure 2.10 Combination of the magnetic fabric with the interpretation of ε_{Nd} data of Housh and McDowell (2005).

Plot illustrates a strong correlation between the linear patterns and ε_{Nd} data and magnetic fabric. This correlation between both data sets strengthens the basement model initially derived from field observations.

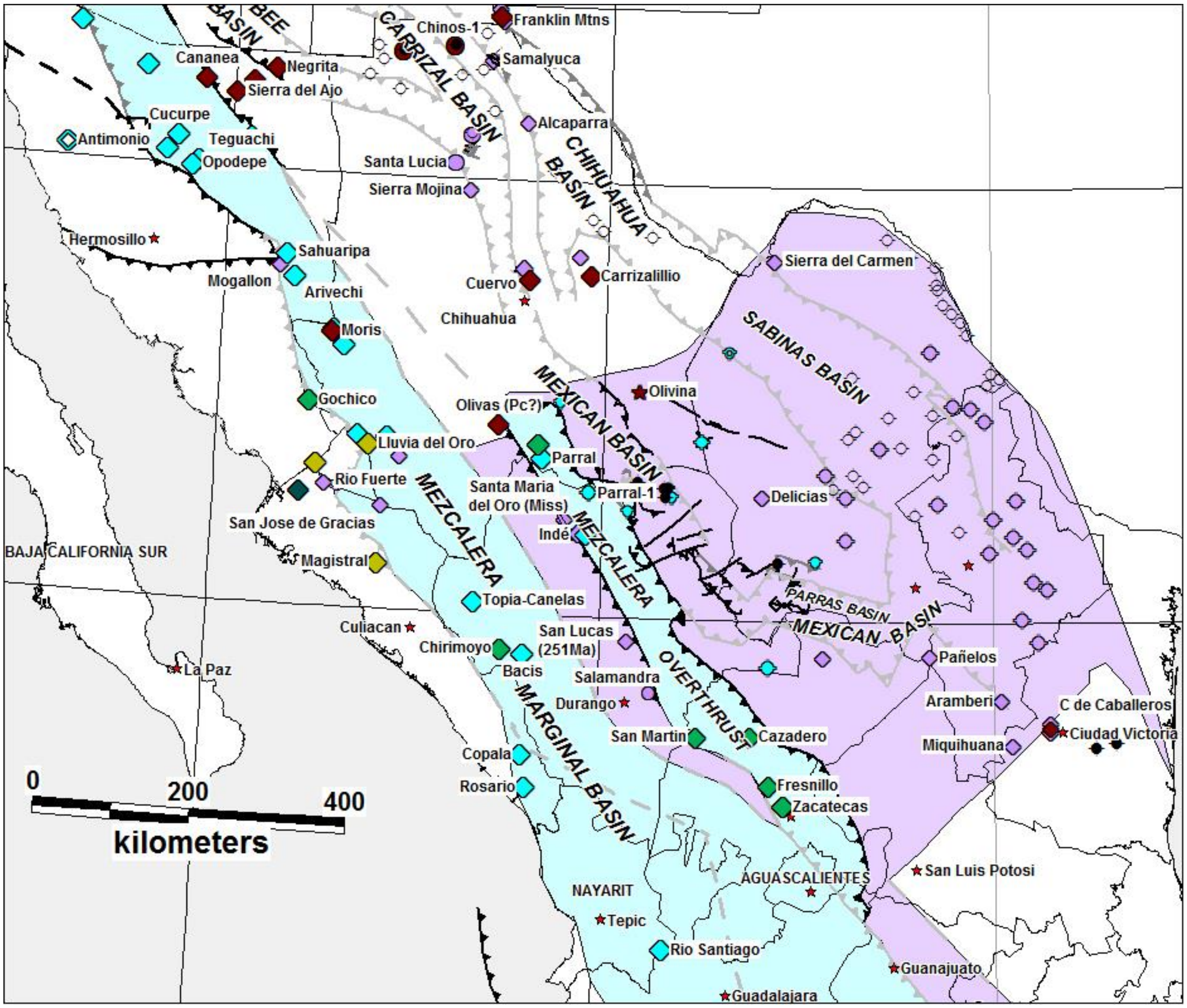


Figure 2.11 Interpreted Paleozoic basement of Mexico and its relationship to the Mezcalera Marginal Basin and Overthrust.

Diamonds and circles distinguish between outcrops and drill intercepts respectively. Blue indicates Jurassic and green indicates Cretaceous. Purple indicates Paleozoic, red-brown Precambrian and blue Jurassic.

CHAPTER 3: MESOZOIC MEZCALERA MARGINAL BASIN

The geologic framework of the Mesozoic Mezcalera basin was originally published as a model for understanding the distribution of mineralization in the newly proposed Guerrero Marginal Basin (Lyons, 2008, see updated version in Appendix B). The Guerrero name was applied to this marginal basin because it was proposed as a replacement for the accreted Guerrero Terrane proposed originally by Campa and Coney (1986). Campa and Coney proposed the Guerrero as an accreted terrane because of major changes across the boundary between continental Mexico and the proposed Guerrero arc accretion. The contrasting geology is also consistent with a continental margin and a continental margin basin as proposed here. The presence of Precambrian basement fragments as an apparent floor to the proposed basin is inconsistent with arc accretion as are the abundant turbidite basal debris flows containing abundant coarse Upper Jurassic carbonate platform fossil assemblages. Coincident arc accretion and extension of the Mexican continent are incongruous tectonically but plate rollback and extension are compatible.

Twenty three new radiometric dates along with many dates from the literature suggest that the well documented Lower to Middle Jurassic Arc the Nazas may have swept west across this marginal basin in the Late Jurassic and continued westward into the position of the Alisitos Arc during the Early Cretaceous. At the end of the Early Cretaceous the arc sweep back across the Mexican continent in the well documented (Damon and others, 1981) sweep of the arc during the Late Cretaceous through Cenozoic.

New mapping at Batopilas, and Moris, Chihuahua supports post Late Jurassic shortening for the newly proposed marginal basin. New mapping at Lluvia del Oro, Chihuahua and Zataque, Sonora-Sinaloa and the determination of two new U-Pb dates indicate that shortening of at least 70 km indicated by the minimum length of a thrust sheet across the marginal basin occurs along the west margin of the proposed marginal basin during the late Cenomanian. Mapping at Salamandra and Indé, Durango along with widely distributed reconnaissance mapping throughout the region and compiled published mapping indicates this Late Cenomanian shortening created the Mezcalera Overthrust with at least 150 km of reach onto the Mexican continental platform.

The development of the marginal basin model calls into question the current Mojave Sonora Megashear (MSM) and California-Coahuila Transform (CCT) hypotheses. No field evidence was encountered that indicates any major trans-continental transform fault has cut across the marginal basin. The original data leading to the MSM and CCT is correct in defining a major fault of 100's of kilometers of left lateral motion but the new mapping and compilations of data suggest that this fault turns south southeast into a coast parallel transpressional fault along the western edge of the marginal basin.

It is recognized that the Guerrero name will probably always be associated with an accreted terrane model but that the name Mezcalera, utilized by Dickinson and Lawton (2001) for a marginal basin in a central segment of this newly proposed basin is more appropriate. Dickinson and Lawton (2001) proposed that the Mezcalera Basin was the source of the strata of the Mezcalera overthrust, but that the basin was overridden by the Guerrero exotic terrane or consumed by subduction erosion. Other names utilized in the northern part of the basin are the Cucurpe Basin (Lawton and others, 2003; Mauel and others, 2011) and the Papago Terrane (Haxel and others, 1980, 1984) in a region of southwestern Arizona and northern Sonora that lacks any known pre-Jurassic crust. In the southwestern part of Mexico, the Arperos Basin (Freydier and others, 1996, 2000; Martini and Ferrari, 2011; Martini and others, 2011, 2014) appears to be the continuation of the Mezcalera basin. The development of the Arperos basin as a back-arc basin in the

Late Jurassic and the inception of Late Cretaceous shortening (94 Ma based on the first detection of continental detrital zircons in the Arperos Basin, Martini and Ferrari, 2011; Martini and others 2011, 2014) correlates well with what has been learned about the Mezcalera Basin. Stronger support for the use of the Mezcalera name comes from its original usage for the Mezcalera overthrust (Araujo-Mendieta and Arenas-Partida, 1986; Aranda-Garcia, 1991) that superimposes deep water and shelf strata from the Mezcalera Basin over chronostratigraphically equivalent platform strata of Chihuahua, Durango and Zacatecas.

This chapter will present new mapping and partial results from exploration drilling of the key area of Batopilas, Chihuahua complemented by reconnaissance studies of mining prospects at Lluvia del Oro and Moris, Chihuahua and Zataque, Sonora-Chihuahua. These new data helped to develop the hypothesis of Mezcalera marginal basin in western Mexico. The prospects align along an east northeast line through Batopilas and are presented as part of a regional cross section hypothesizing on the structural form of the basin.

Following the presentation of these various projects, the hypothesis to be proven is that the accepted Mojave-Sonora megashear in northwestern Sonora can be modeled to turn south southeast into a coast parallel approximately 600 km left lateral transpressional fault. Many published studies along with new data from this study that are consistent with this model are discussed.

Further discussion focuses on the timing of these events along the west coast of Mexico again with a combination of published and new data on timing of post Bisbee Group folding and thrusting event between the termination of deposition of the Bisbee Group (~100 Ma) and the initiation of Tarahumara volcanism (~95 Ma). An important component of the initiation of this transpressional event is the approximate 90 to 150 km thrusting of Upper Jurassic and Lower Cretaceous turbidites and deep shelf strata out of the basin on to the carbonate platforms of the same age resting on Paleozoic age crust of the Mexican craton, the Mezcalera overthrust. This is in part documented by Servicios Geologico Mexicano maps and this study and published logs of PEMEX exploration drilling (Grajales-Nishimura and others, 1992).

Mapping and core logging supports the existence of a 600 to a 1,000 km long inverted basement block. that uplifted after the Mezcalera thrusting. This block, the Durango inverted basement block, is estimated to be uplifted in excess of 1,000 m. The presence of Middle Jurassic volcanism on uplifted, Paleozoic aged metamorphosed crust over a length of 400 km and outcrops of debris flows of schist and platform carbonate fragments in a mud matrix off of the uplifted inverted block into the Late Cenomanian-Turonian Indidura Formation is presented as supporting evidence.

Finally, the spatial association of various types of ore deposits including Mo content of porphyry Cu deposits, Au deposits and tourmaline distribution among others was discussed (Lyons, 2008) in an attached preprint.

INTRODUCTION

The Mesozoic geology of the west coast of Mexico has been difficult to decipher principally because of the extensive volcanic cover of the Eocene through Miocene Sierra Madre Occidental Volcanic Province (SMOVP) and the Late Cretaceous Sonora-Sinaloa Batholith (Fig. 3.1). Recent studies of Jurassic strata in north central Sonora (Mauel and others, 2011) and the mapping completed as part of this study in southwest Chihuahua, southern Sonora and northern Sinaloa have begun to reveal the geologic setting and Mesozoic tectonic history of Mexico’s western coastal belt (Fig. 3.2), as correlations can be made between outcrops exposed in the various canyons dissecting the western margin of the SMOVP.

The southwestern region of Chihuahua is mostly covered by the SMOVP with the only exposures of earlier rock occurring in the deep canyons draining to the west. The Batopilas Silver District contains previously undocumented outcrops of Upper Jurassic marine strata (Wilkerson and others, 1988; Minera Cascabel, 2001), whereas the Moris Gold District consists of a known basement exposure of marine Jurassic strata (Garcia-Cortez and others, 2000; Herrera-Galvan and Cabañas-Villalba, 2004). Lluvia del Oro (Chihuahua), Zataque (Sonora-Sinaloa), and Magistral (Sinaloa) contain strata that lithologically correlate with the Bisbee Group of northern Sonora. At Lluvia del Oro and Zataque, folded rudist-rich fossiliferous limestone beds are separated by a marl and underlain and overlain by 100s or if not repeated 1,000s of meters of mature sandstone sequences with some shale, conglomerate, and tuffs. The carbonate strata could form in many shallow platform environments, but a continental scale clastic source would be required for the thick sandstone sequences observed. To the west lies a volcanic arc (Alisitos) that appears to contribute the observed tuffs but is an unlikely source of the mature sandstones particularly those with Precambrian zircons. To the east lie on the order of 1,000,000 square kilometers of carbonate platforms of the Upper Jurassic Zuloaga Limestones and Lower Cretaceous platform carbonates. Longshore drift could be called upon to bring the sand 600 km south from the main Bisbee depocenter, but the coarser conglomerates would be expected to have been deposited 500 km further north.

For the purposes of this study the Oligocene and Miocene Sierra Madre Occidental Volcanic Province (SMOVP) will be treated as cover. The SMOVP is estimated to cover a region of 1,200 km from the American border to the Trans-Mexican Volcanic Belt and is typically 200 to 300 km wide, approximately 300,000 square kilometers. Many of the exposures of the rocks of interest to this study occur at the bottoms of the many 1,000 to 1,500 m deep canyons that penetrate the SMOVP draining the sierra into the Pacific Ocean and Gulf of California. The SMOVP is estimated to exceed 2,000 meters in thickness over much of the area based on exposures in these canyons.

PAST STUDIES AND MODELS

During the 1990's this study initially focused on utilizing the widely accepted hypothesis of 800 to 1,000 km of left lateral transverse motion across northern Mexico along a proposed Mojave-Sonora Megashear (Silver and Anderson, 1974, Anderson and Silver, 1979, 2005, Jones and others, 1995) as a guide for mineral exploration based on potential fault splays, fracturing and brecciation lateral to such a major fault. Anderson and Silver proposed the motion occurred between the large Middle Jurassic outpouring of silicic magmatism and the deposition of Upper Jurassic marine strata and moved the Caborca Terrane into its present position at that time. Various proposals for similar structures transverse to Mexico have been made. The most recent proposal for a similar structure being the California-Coahuila Transform (Fig. 3.3b; Dickinson and Lawton, 2001) that is proposed to have moved the Caborca Terrane into its present location during the earliest Permian.

A second major model attempting to explain elements of Mexico's geology was the terrane model of Campa and Coney (1983). Although the Mojave-Sonora Megashear (MSM) was not included in their map, they recognized the Caborca terrane as a possible allochthonous terrane that migrated south approximately 700 km along the MSM from southern California (Fig. 3.3a). The extension of the North American craton into northern Mexico was referred to as the Chihuahua terrane and the Paleozoic crust continuing from the Appalachian-Ouachita orogenic belt was referred to as the Coahuila terrane (Campa and Coney, 1983). Along the southwest margin of the Chihuahua and Coahuila terranes and continuing south of the Caborca terrane, Mesozoic sedimentary and volcanic arc strata named the Guerrero terrane was interpreted as having been accreted to the Paleozoic and older crust during the Late Mesozoic and Early Cenozoic. This terrane model was followed by later revisions such as by Sedlock and others (1993) and Dickinson and Lawton (2001). Sedlock and others (1993) compiled basement radiometric ages and revised the diagrammatic sections of Campa and Coney but broke with 10 years of tradition and attempted to change the terrane names of Campa and Coney to indigenous tribe names resulting mostly in confusion in the literature from lack of uniform usage. Dickinson and Lawton (2001) sought to resolve the resulting confusion by combining both different terminologies producing longer even less used names. They renamed of the Guerrero Terrane to Guerrero Super Terrane to recombine the various subdivisions Sedlock and others (1993) had introduced. Based on work in California (Dickinson, 2000), Dickinson and Lawton (2001) also reinterpreted the Mojave-Sonora megashear as a similar but older Early Permian fault, the California-Coahuila transform along which the Caborca Terrane migrated. Details of this model continue to be topics of discussion (Wetmore and Paterson, 2003).

Upper Jurassic marine strata makes up the oldest outcrops along an extensively documented belt subparallel to the west coast of Mexico. Haxel and others (1980, 1984) recognized a potential Jurassic basin, the Papago Terrane, that lacks autochthonous Pre-Jurassic outcrops and consists of Jurassic continental sandstone interfingered with marine shale. The complete Jurassic section of the Cucurpe, Sonora area has most recently been studied by Lawton and others (2003), and Mauel and others (2011). The Cucurpe basin displays the same distinctive lack of autochthonous Pre-Jurassic outcrops as does the

Papago terrane immediately to north and both were presented as a single basin by Mauel and others (2011). The marine strata of the Middle Jurassic Lily Formation west of Nacozari (McAnulty, 1970, Gonzalez-Leon and others, 2009) and an unnamed black shales east of the Opedepe below the Bisbee Group (Valenzuela-Navarro and others, 2005) continues this belt to the southeast. In the Sahuaripa-Arivechi, Sonora area more Upper Jurassic ammonite-bearing black shales are documented (Pubellier and others, 1995; Garcia Cortez and others, 2000; Teran Martinez and others, 2005). In the Moris, Chihuahua area, Jurassic strata surrounding a basement block is included in the Tecoripa 1:250,000 scale quadrangle (Garcia Cortez and others, 2000) and the Moris (Herrera-Galvan and Cabañas-Villalba, 2004) and Yepachic (Espinosa and Canizal, 2007) 1:50,000 scale quadrangle maps. Jurassic strata were first lithologically correlated with ammonite-bearing strata southwest of Pilar de Moris, west of Moris (Garcia Cortez and others, 2000) and later dated with Upper Jurassic microfossils (Herrera Galvan and Cabañas Villalba, 2004). The next known Jurassic marine strata are that of Batopilas, Chihuahua 130 km south southeast of Moris (Lyons, 2008) that along with probable Jurassic strata observed north of Reforma, Chihuahua fill in a large gap between Moris, Chihuahua and Topia, Durango. Similar Jurassic strata are documented at Topia, Durango (Esquer Mundo and others, 2001) and Copala and Rosario, Sinaloa (Garcia-Padilla and others, 2000; this study). Additional undated similar black shales were observed in Jalisco along the Rio Santiago north west of Guadalajara during this study.

The boundaries of the terranes as proposed (Fig. 3.3b) by Dickinson and Lawton (2001) are plotted over the distribution as interpreted by this study of the Jurassic and Lower Cretaceous shelf deposits (Fig. 3.4). These belts of Jurassic and Lower Cretaceous strata clearly cross the boundaries proposed by Dickenson and Lawton (2001). In addition the belt of Paleozoic basement between the now proposed marginal basin and the Mezcalera overthrust lies mostly within their proposed Mid-Cretaceous suture zone. The presence of Mid-Jurassic Nazas strata is interpreted from the fact that Cenomanian Indidura lies on top of a volcanic unit in drill hole Salamandra-18 (Fig. 3.4). The Nazas strata is lithologically similar to dated Nazas tuff at Rio Nazas (Lawton and Molina-Garza, 2014) and at Sierra Ramirez (this study see Appendix A sample JLSR-1). Underlying this Nazas correlative tuff at Salamandra-18 is Paleozoic schist equivalent to schist dated at San Lucas at 250 Ma (Iriondo and others, 2003). The relationship was also noted at Indé as part of this study. These Nazas over schist relationships contradict the model of it being part of an accreted suture zone but indicate that these Paleozoic rocks (Iriondo and others, 2003) were part of the continent during the Jurassic.

Lower Cretaceous strata are divided into two main facies, the marine reworked deltaic strata of the Bisbee Group located in northern Sonora and deep water shelf strata found in northern Sinaloa. The Bisbee Group is well documented in northern Sonora (e.g. Mauel and others, 2011). The Lower Cretaceous deep water shelf strata are best documented as part of the Mezcalera overthrust to the east (this study), but it was observed in place during this study at Gochico in southeastern Sonora, and Chirimoyo in southwestern Durango in addition to the Mezcalera occurrences.

The thrusting of the Caborca Terrane basement and supra crustal strata over this belt of Jurassic and Lower Cretaceous basin strata along the western edge of a proposed marginal basin is well documented from the Arizona border (Haxel and others, 1984) through Cucurpe (Mauel and others, 2005), Opedepe (Valenzuela-Navarro and others, 2005) Sahuaripa-Arivechi area (Pubellier and others, 1995) of Sonora.

The initial description of this proposed Jurassic marginal basin was published as the geologic setting of metal anomalies such as the western Mexico gold belt, and the distribution of copper, molybdenum and boron (Lyons, 2008 see Appendix B). The basin was interpreted as having some rift basalts and deeper seated igneous rocks in its floor based on scattered outcrops of such rocks within 10 km northwest of the San Francisco Mine, Sonora and along the Cucurpe road south of the Nogales-Hermosillo highway. These oceanic rocks are typically twice as anomalous in Au (all still single digit ppm Au) and the marine shales that fill the basin are typically more anomalous in B and Mo. Marine shale contains most of the earth's crustal boron and typically elevated levels of Mo.

An underlying conclusion was that no ± 1,000 km offset northwest-trending fault having both Permian and Jurassic motion was indicated as transecting the Middle Jurassic through Lower Cretaceous basin as proposed by the Mojave-Sonora Megashear hypothesis (Silver and Anderson, 1974; Anderson and Silver, 2005) and the similar California-Coahuila Transform proposed by Dickinson (Dickinson, 2000; Dickinson and Lawton, 2001). The estimated reach of the Mezcalera Thrust onto the central Mexican continental platform of 150 km indicates shortening of at least this magnitude. Both the Upper Jurassic and Lower Cretaceous deep water turbidites, thrust over similar age platform carbonate strata was most likely the result of the transpressional emplacement of the Caborca crystalline basement and associated supracrustal strata. This transpressional event produced isoclinal folding of the Bisbee Group and older strata as well as the thrusting of the Caborca basement and supracrustal Precambrian and Paleozoic strata over the Bisbee Group and Upper Jurassic basin filling strata (Mauel and others, 2011: this study).

The precise timing of the initiation of this event has not been determined. It appears to be bracketed between the beginning of the Cenomanian and the end of the Turonian. Undeformed Tarahumara volcanic rocks appear to be at least as old as 90Ma (McDowell and others, 2001; Gonzalez-Leon and others, 2011) and possibly older. These tectonic signatures indicate a Cenomanian through Turonian initiation of shortening. Disharmonic folding between the Upper Jurassic and Lower Cretaceous strata and deformation of late Jurassic dikes has been interpreted (Dickinson and Lawton, 2001; Mauel and others, 2011) as two separate shortening events, one in the Jurassic and the second in the Late Cenomanian. Another possible explanation is different responses to the shortening event between the Cucurpe shale and the Bisbee Group conglomerate and sandstone.

It appears that significant shortening was not active until the end of the Cenomanian (Grajales-Nishimura and others, 1992; Pubellier and Rangin, 1995; Mauel and others,2011). An angular unconformity is overlain by Late Cenomanian through Coniacian (~93 to 85Ma) Tarahumara volcanic rocks (McDowell and others, 2001; Gonzales-Leon and others, 2011; this study). A possible angular unconformity was recognized between the Upper Jurassic Cucurpe Formation and the Bisbee Group in the Cucurpe area (Mauel, 2011). In the many years of this study the Cenomanian-Coniacian Tarahumara (~95 to 85 Ma) has always been separated from the Maastrichtian-Paleocene Laramide (~70 through 50 Ma). The six dates of McDowell and others (2001) shows a bimodal distribution of ages within what they refer to as the Tarahumara and 28 U-Pb, 9 K-Ar and 1 Ar-Ar dates obtained by Gonzalez-Leon and others (2011) are all from the younger suite that they refer to as both the Tarahumara and Laramide volcanism. The east dipping volcanic rocks at Batopilas are cut by 85 to 88 Ma stocks and are considered to be of Tarahumara age in this study.

Southwestern Durango, Sinaloa and southern Zacatecas have been included in the Guerrero Terrane (Campa and Coney, 1983; Dickinson and Lawton, 2001) of southwest Mexico. SGM geology maps generally follow this convention with some confusion related to whether Paleozoic outcrops along the east side of the SMOVP are part of the

Guerrero Terrane or Mexican Paleozoic basement. Further south Martini and Ferrari, (2011); and Martini and others, (2011, 2014) have come to similar conclusions. This indicates that the Arperos basin is the Southern Mexico analogue to the Mezcalera Marginal Basin and tectonic shortening and uplift initiating at about 94 Ma or late Cenomanian.

In the Batopilas, Chihuahua area is a newly discovered occurrence of Upper Jurassic marine strata added as a part of this study (Lyons, 2008). Collectively these outcrops form a belt of similar Jurassic and Lower Cretaceous strata found along the west coast of Mexico from northern Sonora at least as far south as southernmost Sinaloa with field reconnaissance observing similar outcrops into Jalisco.

A review of fossil studies in Sonora (Almazan-Vazquez, 2000) indicates two main areas of Jurassic ammonites: those deposited on the Caborca basement block in the Sierra el Alamo and those deposited in a belt of marine slope and rise strata between the Caborca basement block and the North American Craton. The Mesozoic strata on the Caborca block includes Upper Triassic and Lower Jurassic ammonites. Only Middle and Upper Jurassic ammonites and microfossils are known so far from the belt of marine slope and rise strata underlying the Lower Cretaceous Bisbee Group at Cucurpe, Sonora (Villasenor and others, 2005), Nacozari, Sonora (McAnulty, 1970), and Arivechi, Sonora (Almazan-Vazquez and Palafox, 1985) and El Pilar and Moris, Chihuahua (Garcia-Cortez. and others, 2000; Herrera Galvan and Cabañas-Villalba, 2004). Middle Jurassic ammonites are reported at Topia, Durango (Esquer-Mundo and others, 2001). A suite of undated ammonites, belemnites and gastropods have been collected at Batopilas from marine strata interbedded with volcanic debris that dates at 149Ma by U-Pb from zircons (this study, see sample JL-B-02, Appendix A), essentially identical to dates obtained in the Cucurpe Basin (Lawton and others, 2003; Mauel and others, 2011).

The first regional map in the area, centered on the Batopilas area, was the dissertation of Bagby (1979). This was followed by studies of Wilkerson (1983) and Wilkerson and others (1988) on the Batopilas District geology. They did not recognize the fossiliferous Jurassic strata that host much of the mineralization and comprise most of the center of the district but mapped them as a dacite.

Servicio Geologico Mexicana (SGM) has published 1:250,000 scale geologic maps for all of the areas discussed and 1:50,000 scale geologic maps of most areas. The maps assist somewhat in understanding the regional geology but are all too often unreliable. For example, the SGM G13-A41 Batopilas geologic quadrangle map (1:50,000 scale, Minera Cascabel for SGM, 2001) does not recognize the presence of Upper Jurassic strata and combines these fossiliferous strata with Upper Jurassic, Early Late Cretaceous and Eocene volcanic and intrusive igneous rocks into one unit in the Batopilas area. The mapping carried out under contract for the SGM by Minera Cascabel (Minera Cascabel company files, discussed further below) indicated some Jurassic strata near Batopilas, but this was deleted in the final version possibly deferring to the maps by Bagby (1979) and Wilkerson and others (1988).

Other SGM maps covering projects included here are the Tasajeras G12-B59 1:50,000 scale quadrangle (Aparicio Cordero and Escamilla Torres, 2004) that covers the Lluvia del Oro area and the Baca G12-B58 1:50,000 scale quadrangle (Quevedo Leon and others, 2009) that includes the Zataque prospect area. The Tasajeras quadrangle includes the units, KaMCz, JtKapMa and JtKapCz that contains andesite and limestone. These units are a mixture of Jurassic submarine strata and Lower Cretaceous andesitic volcanic strata, Lower Cretaceous marine reworked fluvial sandstone, shallow reef and lagoonal carbonates, and waterlain tuffs. The Baca map includes an Upper Jurassic through Lower Cretaceous unit JtKaA-Cz, that reportedly consists of andesite and interbedded limestone and sandstone. These different strata are not subdivided on the Baca G12-B58 map, but limestone was apparently added later as difficult to see outlines labeled JtKapMCz on the Tasajeras G12-B59 map.

The most recent studies are the regional study of the Jurassic Marginal Basin of Lyons (2008) and Lyons and others (2012) that recognized the Jurassic age of much of the Batopilas District and the thesis by Kallstrom (2012) that focused on the fluids and metal sourcing of Batopilas veins.

K-Ar dating and air photo mapping in the SMOVP along the Durango-Mazatlan Highway (McDowell and Keizer, 1977; Swanson and others, 1978), in the Batopilas, Chihuahua region (Bagby, 1979), the Tomochic, Chihuahua area (Swanson, 1977) and the Mulatos, Sonora area by this author (Barton and others, 1995) document the Tertiary structural setting of the volcanic rocks of the region. Although the focus of this study is on the pre-Oligocene rocks beneath the SMOVP, the studies of structural setting of the volcanic strata have proven a useful guide.

GEOLOGIC SETTING

Most of the region of interest in this study is deeply buried by the Sierra Madre Occidental Volcanic Province Eocene through Miocene volcanic field (Fig. 3.5). The pre-volcanic exposures studied lie mostly in 1,500 to 2,000 m deep canyons transecting the SMOVP or along its western outcrop margin. Removing the SMOVP layer from the map (Fig. 3.6) allows estimating the extent of the proposed marginal basin and the Durango Inverted Basement Block. The continuity of Middle through Upper Jurassic marine strata found from exposures near Cucurpe to Batopilas across the proposed Mojave-Sonora structure led to this concept of a coast parallel Jurassic basin. Upper Jurassic and Lower Cretaceous strata make up the majority of the exposed marine strata within the proposed basin. A limited number of older basement fragments show evidence that they existed as a high relief (topographic relief measures a minimum of 700 m at Moris) basement around which the Upper Jurassic marine strata were deposited, particularly at Moris, Morelos and San Jose de Gracias, Chihuahua and Rio Fuerte, Sinaloa (Fig. 3.7). The Jurassic marine strata exposures continue southward from south central Arizona with an inter-fingering of continental sandstone and marine shale (Papago Terrane of Haxel and others, 1980 and 1984). The northwest structural fabric of the outcrops older than Upper Cretaceous in both northeastern Sonora and in southwestern Chihuahua suggests by their similarities that the strata in both regions underwent the same tectonic forces. The axis of these Lower to Upper Jurassic outcrops and their fold and thrust fabric observed during this study and documented (Mauel and others, 2011; Pubellier and others, 1995) cuts across the proposed trace of Mojave-Sonora Megashear (MSM). An attempt to understand how the isolated outcrops available in southwestern Chihuahua relate to the better exposed geology of northern Sonora needs to be based on how their stratigraphic and tectonic history relate. Exposures of Precambrian through Paleozoic basement occur mostly in northern and western parts of Sonora (Figures 3.1 and 3.2). East of Cananea various outcrops of 1.65 Ga Mazatzal Provence and 1.44 anorogenic granites occur (Fig. 3.6 and Fig. 3.7). Between the North American Craton Precambrian and Paleozoic outcrops of the Cananea District and the overthrust of Precambrian and Paleozoic from the Caborca Terrane south of Cucurpe, the oldest exposures are Lower Jurassic volcanic and Upper Jurassic marine strata (Maul and others, 2010; this study). Some blocks of probable Caborca strata and basement are mapped in the Jurassic strata near the Caborca overthrusting of the Jurassic and Lower Cretaceous basin fill (Mauel and others, 2011). Upper Jurassic deep marine strata are well documented underlying the Lower Cretaceous Bisbee Group in the Cucurpe region of north central Sonora (Mauel and others, 2011).

Additional outcrops of equivalent Upper Jurassic strata have been documented in a belt continuing from the Papago Terrane (Haxel and others, 1980 and 1984), southwest of Nogales in northern Sonora, south through the Cucurpe and Teguachi areas and to the southeast of the Arivechi area (Fig. 3.5 and 3.6). Tightly folded Lower Cretaceous Bisbee Group strata overlies the Jurassic strata in most areas of northern Sonora. Complex Cenomanian folding and thrusting typifies the boundary between the Upper Jurassic and the Lower Cretaceous along the east edge of the Caborca basement block at Cucurpe (Mauel and others, 2011), Opedepe (Valenzuela-Navarro and others, 2005) and Sahuaripa (Pubellier and others, 1995). Isoclinal folding of the Bisbee Group crops out along the margin of the basin with the North American Craton in the Bellota range southeast of Cananea (this study) and in the Nacozari, Sonora area (McAnulty, 1970) whereas the Bisbee Group displays high angle reverse faults to the east of the basin boundary.

The focus of this study will be a series of small mining districts; the Zataque, Sinaloa, Au district and the Lluvia del Oro, Chihuahua Au district west southwest of the Batopilas, Chihuahua Ag district. The mining districts continue across the proposed marginal basin and will be connected in a regional cross-section that is then projected to the east side of the SMOVP where outcrops are interpreted as the eastern boundary of the marginal basin. Mapping and dating at Moris, Chihuahua is included to better link Batopilas with the Jurassic of the Arivechi-Cucurpe-Papago Basin belt of rocks.

BATOPILAS SILVER DISTRICT, CHIHUAHUA; GEOLOGY AND MINERALIZATION

The Batopilas Silver District (Fig. 3.8) is an important new locality of Upper Jurassic marine strata with a significant submarine volcanic component. Batopilas is located 100 km south of Creel, Chihuahua by road in southwestern Chihuahua in one of many deep canyons dissecting the volcanic plateau of the Sierra Madre Occidental Volcanic Province (SMOVP). Batopilas sits along the Batopilas River at about 600m elevation, 1500m below the tops of the surrounding volcanic mesa of the SMOVP.

Batopilas Introduction

The numerous outcrops in windows through the SMOVP suggest continuity of the Jurassic and Lower Cretaceous strata and leads to the model of a previously unrecognized Jurassic basin (Lyons, 2008; this study). This basin continues unbroken from southwestern Arizona well into the region of southwestern Mexico previously modeled as an accreted terrane, the Guerrero Terrane. The recognition of Batopilas as a new Upper Jurassic exposure (Lyons, 2008; this study) strengthens this model. The Upper Jurassic age is based on similarities (T.F. Lawton, personal communication) between ammonites at Batopilas and those dated as Upper Jurassic found at Cucurpe, Sonora (Villaseñor and others, 2005;) and detrital zircon dates (this study, see Appendix A, sample JL-B-02,) from the belemnite-bearing volcanic detritus-rich strata between two submarine flow domes in the center of the district.

Batopilas Previous Work

The earliest major mapping in the region was Bagby (1979) who addressed regional geology. This was a very coarse first pass attempt at understanding the regional geology under conditions of difficult accessibility. Bagby recognized three units near Batopilas; the Upper and Lower Volcanic Sequence and a plutonic suite. Bagby also carried out the first radiometric dating in the Batopilas Silver District, a 50 Ma Rb-Sr date on the stock later named the Dolores by Wilkerson (1983), as well as an 85 Ma K-Ar dated stock cutting subaerial deposited andesite in the northeast corner of this study area.

Bagby's study mostly focused on the petrogenetic evolution of the igneous systems with little data specifically on Batopilas.

The second major work focused on the Batopilas Silver District was by Wilkerson (1983; Wilkerson and others, 1988). Wilkerson (Fig. 3.9, 3.10) followed the regional subdivision of Bagby (1979) with a plutonic suit, Lower and Upper Volcanic Series (instead of sequence as used by Bagby). The Plutonic Suite was subdivided by Wilkerson (1983) from oldest to youngest into the Pastrana Dacite, the Dolores Micro-Diorite and the Tahonas Granodiorite (Fig. 3.9; Fig. 3.10, Wilkerson and others, 1988). Wilkerson and others (1988) published a K-Ar date on the Dolores of 51.6±1.1Ma which was consistent with the 50 Ma Rb-Sr date from Bagby (1979). To the east Wilkerson mapped two Tertiary volcanic units as his Lower Volcanic Sequence, the El Arenal and San Jose flow breccias; he indicated they were capped by conglomerates and the Yerbanis rhyolite welded tuffs of the SMOVP. A block of strata in Wilkerson's Pastrana dacite unit including an ammonite fossil were proposed to be rafted blocks of strata, possibly from the overlying volcano-clastic units. Wilkerson surmised a zonal relation of the silver mineralization to one of the Tahonas granodiorite stocks on the southwest side of the district. The Batopilas District is situated in the southwest corner of the San Juanito 1:250,000 SGM quadrangle map (Maldonado-Lee and others, 2000) where only Late Cretaceous andesite and Paleogene and Neogene welded tuffs are indicated, cut by small stocks of similar ages.

This work recognizes the unpublished work of Roberto Sanchez G. who first mapped several square kilometers of Jurassic clastic strata in the heart of the district (unpublished Cascabel S.A. de C.V. company map, 2000). The publication of the Batopilas quadrangle (SGM geologic quadrangle G13A41, 2001) by Servicio Geolóico Mexicano reportedly included his work but does not indicate any Jurassic sedimentary or volcanic rocks in the Batopilas Silver District (Fig. 3.11). Although this study has expanded the area of Jurassic strata and added detail to Sanchez's work, the observation of sedimentary strata that lithologically correlated with known Jurassic strata to the north (Pubellier and others, 1995) was an important contribution towards a better understanding of the district.

Terminology

The terms sequence, series and suite used in previous reports need to be addressed as defined in the Glossary of Geology. The usage of "sequence" by Bagby (1979) appears to refer to an informal lithostratigraphic unit of greater than group or super group status bounded by interregional unconformities. The use of "series" for the same two lithostratigraphic units by Wilkerson and others (1988) is stated to be a misuse by the Glossary of Geology and it suggests group as the proper usage. Both Bagby (1979) and Wilkerson and others (1988) use suite for the collection of Batopilas plutonic rocks. This usage is only correct in the broadest sense of a collection of plutonic rocks from the same region. They are unlikely to be co-magmatic with Bagby's age range of 85 to 45 Ma. McDowell and Keizer (1977) proposed the term upper volcanic supergroup for what Bagby (1979) termed the Upper Volcanic Sequence and Wilkerson and others (1988) termed Upper Volcanic Series. The lower volcanic sequence or series (Bagby and Wilkerson respectively) was referred to as the lower volcanic complex by McDowell and Keizer (1977). Lacking sufficient mapping and ages (radiometric and fossils), complex is a suitable term but as age and field relationship issues are resolved more appropriate terms such as formations, groups and suites should be applied.

The terms Upper and Lower volcanic sequence or series need to be dropped from the nomenclature because in practice they are used to divide mostly intermediate older rocks from the mostly rhyolitic outpourings of the Sierra Madre Occidental Volcanic Province. In reality, as used, these intermediate composition rocks of the lower volcanic complex range in age from Jurassic (149 Ma this study) to early Late Cretaceous Tarahumara Formation and Sonora-Sinaloa Batholith (Fig. 3.1; 90 to 85 Ma, Turonian-Coniacian, McDowell and others, 2001 and this study) Late Cretaceous through Paleocene volcanic rocks and stocks (72 to 55 Ma, Laramide, McDowell and others, 2001) to Eocene age flows, tuffs and vents (51 to 46 Ma at Batopilas, this study and Swanson and others, 1977 at Durango 35 km west of the Salamandra locality both on Fig. 3.5). Serious effort should be directed at distinguishing the proper age subdivisions for the widely misused terms lower volcanic sequence, series and complex. It could be argued that the different ages are difficult to distinguish but using Batopilas as an example, folding and thrusting are prominent in the Jurassic strata, whereas the Tarahumara is only faulted and tilted.

The basin terminology is included here to aid in understanding the setting of the volcanic arcs. The basin terms considered here are marginal basin, forearc basin and back-arc basin. The term marginal basin is applied to strata accumulation along a passive continental margin but also to forearc basins. In both cases it is being used to describe an asymmetric basin accumulating sediment along the margin of a continent. Forearc and back-arc basins are applied to the subducting and overriding side of the arc respectively. The proposed basin accumulated significant craton-derived turbidites, volcanic debris and deep marine shale during the Middle to Late Jurassic. Middle Jurassic volcanism was active to the east on the Mexican craton. During the Upper Jurassic, data to be presented indicates volcanism was active within the basin. A major reworked alluvial fan and deltaic complex, the Lower Cretaceous, Bisbee Group, accumulated in the southwestern United States and northern Sonora and thin bedded deep shelf strata accumulated in southern Sonora. No evidence of Early Cretaceous venting was documented within the basin in previous work or during this study; however two distal tuffs with U-Pb ages of 138 and 124 Ma from within the Bisbee Group Morita Formation (this study, see samples JL-AS-1 and 2 and JL-MO-01, Appendix A and Supplemental data) within the basin document volcanism that by elimination would have had to have come from the west from what is known as the Alisitos Arc. During the Late Cretaceous the arc swept eastward with the Sonora-Sinaloa batholith cut the basin and deposited the sub-aerial Tarahumara volcanic rocks over the basin.

From the Pemo-Triassic through the Lower and Middle Jurassic, the arc cuts the continental crust. The basin, although accumulating sediment marginal to the continent, is situated as a forearc basin west of the arc. It changes its position in relation to the arc in the Upper Jurassic as the arc migrates to the west through the basin and it becomes an intra-arc basin. In the Lower Cretaceous the arc reaches its westernmost position and is referred to in the literature as the Alisitos Arc that is now located in Baja California. At this point in time, the basin has become a back-arc basin. All that is observed during this study of the Alisitos Arc on the mainland are distal tuffs referred to above. Tectonically, folding and thrusting are not obvious within the basin, and most deformation during the Jurassic and Early Cretaceous maybe limited to deformation from the sweeping of the arc across the basin. This quiescence comes to an end in the Late Cenomanian when a change in the relationship between the subducting ocean floor and the Mexican craton occurs producing a much greater rate of subduction, concurrent eastward migration of the arc, major tectonic shortening of the marginal basin and eventually shortening of the intracratonic basins to the east. The basin strata are in part thrust out-of-the-basin in the Mezcalera Overthrust in the interval of less buoyant Paleozoic crust. The term marginal basin is normally applied to passive margins but because this basin has been a forearc, intra-arc as well as a back-arc basin through time, the term marginal basin will be utilized here as a less specific term applying to its marginal position in relation to the Mexican continent rather than in its changing position in relation to the migrating arc. Forearc, intra-arc and back-arc will be used for specific applicable time periods.

Batopilas Regional Setting

The Batopilas Silver District is located at the midpoint of documented outcrops of the Jurassic marginal basin (Fig. 3.2; Lyons, 2008) that is mostly buried by the SMOVP. Small windows expose basin strata from the Arizona-Sonora border to at least as far south as 23°N, but it probably continues to Mexico's southern coast. The Nazas over Paleozoic schist found in outcrops at Indé and drill core at Salamandra, Durango (Fig. 3.1) show evidence of limestone and schist debris being shed into the Cenomanian Indidura Formation. This suggests that the basin is bound on the east by normal faults of a rifted margin that now have been inverted. This structural margin in Durango projects under the SMOVP in a north-northwest direction aligning with the structural boundary between the Cananea mineral trend in northeast Sonora and the marginal basin recognized as the Papago Terrane (Haxel and others, 1980 and 1984) and the Cucurpe Basin (Mauel and others, 2011) that lies, at least in part, on extended continental crust. It has been proposed (Lawton and others, 2003) that this basin is actually a series of small grabens, but the deep marine character of deposition and andesitic chemistry of the coeval volcanic rocks (as opposed to rift basalts) suggests that it is a larger marginal basin feed by subduction-related volcanism. No evidence for physical breaks in the basin have been documented in the literature or found during this study. The Francisco Gneiss along Mexico's coast (Fig. 3.7), west of Batopilas has been isotopically interpreted as derived from Triassic rift-related volcanism (Keppie and others, 2006) but it lies on the west side of the transpressional fault (Sonora-Sinaloa Transpressional Fault, Fig. 3.2) as indicated in this study.

Thin bedded to laminated marine shale and tuffaceous strata are draped over a basement block of Precambrian gneiss and granite through Paleozoic quartzite and carbonates platform strata at Moris, Chihuahua. These marine strata are dated as Upper Jurassic based on one ammonite from similar strata 25 km southwest side of Moris (Garcia-Cortez and others, 2000). The basement blocks are consistent with blocks of extended crust. A granite cutting the gneiss lying unconformably under the Paleozoic strata yielded a U-Pb age of 1.44 Ga, correlative with the anorogenic granites of northern Sonora and Arizona. This date indicates the gneiss is Mazatzal or older age crust.

To the south of the Batopilas area, a belt of Paleozoic strata (Fig. 3.5 and 3.7) including Fuerte, Sinaloa, assigned to the Cambro-Ordovician (Vega-Granillo and others, 2008; 2011) San Jose de Gracias (Poole and others, 2005) continues across most of the Pre-Eocene exposure between the coast and the SMOVP and then continues at least as far south as Mazatlan in isolated outcrops. These basement occurrences have been proposed as evidence that the Paleozoic strata is continuous between the Appalachian-Ouachita and west coast (for example Roberts Mountain strata of Nevada, Poole and others, 2005). Their isolated occurrences surrounded by outcrops of Jurassic deep marine strata are also consistent with extended crust derived from the adjacent Ouachita age crust of the Central Highland of Mexico. The Jurassic marginal basin strata are projected to the east beneath the SMOVP. Sparse outcrops of undated deep shelf marine strata have been observed in southern Sonora at Gochico and in western Durango at Chirimoyo (Fig. 3.7). Lithologically they correlate with the slope strata of the Mescalero Overthrust Belt which crops out from north of Parral, Chihuahua, through much of western Zacatecas and are dated at Parral by PEMEX (Eguiluz and Campa, 1982; Aranda and others, 1988) as

Lower Jurassic through Lower Cretaceous. This overthrust is interpreted as Lower Jurassic through Lower Cretaceous strata thrust on to the continent from the Jurassic-Lower Cretaceous marginal basin by the Cenomanian shortening event indicated by thrusting and folding in the Batopilas Jurassic and Lower Cretaceous strata throughout the region.

The distribution of fragmented platform strata on Precambrian crust to the north of Batopilas and Paleozoic basin strata to the south of Batopilas supports a model of a basin floor of extended crust along the Mesozoic crustal margin of Mexico. Furthermore, the distribution of this crust matches the crustal distribution in the craton, suggesting little or no lateral transport since the Triassic.

One pre-Cretaceous shortening event is believed to have affected Mexico's Jurassic western marginal basin as reported in the Cucurpe, Sonora region with deformation in the Jurassic strata and dikes that do not carry through to the overlying Bisbee Group (Dickinson and Lawton, 2001; Mauel and others, 2011). The most widely observed shortening event is a Late Cenomanian shortening event which has been documented from the southwestern USA (Haxel and others, 1980 and 1984) to the Cucurpe region to the Sahuaripa region (Pubellier and others, 1995) and southeast to Batopilas, (this study). This Late Cenomanian event appears to be the driving mechanism for the Mescalero Overthrust belt and the overthrusting of the Caborca and Cortez Terranes over the marginal basin strata.

Batopilas Radiometric Dates

The majority of ages determined during this study were done with U-Pb on zircons. One Re-Os date was obtained on molybdenite from a quartz molybdenite vein cutting a quartz monzonite dike along the Roncesvalles vein. The dates are compiled on Table 3.1 and in Appendix A. The analytical data can be found in the Supplemental Files

Table 3.1 List of Batopilas Dating Samples, Descriptions, Locations, Age and Sample number.

SAMPLE_NO	DESCRIPTION	EAST	NORTH	DATE	ERROR	N=	TECH	LAB_Analysist
JL-B9-M1	Qtz monzonite porphyry hosts JL-B9-M1A	227,563	2,993,520	88.1	±1.1	34	U-Pb	Boise State, V.Valencia
JL-B9-M1A	Qtz Mo vns cuttiing	227,609	2,993,493	84.4	±0.4	1	ReOs	U of Arizona, Barra
JL-B9_M2	Injected Qtz Monz Por in bx dike	227,535	2,993,577	54.9	±0.8	34	U-Pb	Boise State, V.Valencia
JL-B9-M3	Qtz monz porph cutting Dolores diorite	226,692	2,992,564	55.2	±0.8	29	U-Pb	Boise State, V.Valencia
JL-B9-L1	Qtz latite porph cutting qtz monz porph	227,209	2,991,784	28.9	±0.5	33	U-Pb	Boise State, V.Valencia
JL-B9-M4	Qtz monz porph + qtz stockwork flooded	226,658	2,991,258	88.1	±1.3	32	U-Pb	Boise State, V.Valencia
JL-B9-M5	Qtz-monz-porph Kspar-epidote Alt	226,711	2,991,401	88.7	±1.8	32	U-Pb	Boise State, V.Valencia
JL-B9-L3	Latite-porph dike	226,828	2,991,436	72.7	±0.9	30	U-Pb	Boise State, V.Valencia
JL-B9-M6	Quartz-monzonite-porphyry at Batopilas	228,182	2,992,005	86.8	±1.1	30	U-Pb	Boise State, V.Valencia
JL-B9-M7	Qtz-monzonite-porphyry on Animas road	228,710	2,995,660	87.8	±1.0	30	U-Pb	Boise State, V.Valencia
JL-B9-M8	Qtz monz-porph Core BA08-24; 556m	227,657	2,994,649	88.2	±1.2	32	U-Pb	Boise State, V.Valencia
JLB-V-1	Satevo Rhyodacite	223,651	2,989,721	46.8	±0.6	30	U-Pb	U of Arizona, V. Valencia
JLB-L-1	Qtz-latite-porph cutting Minas Member	228,648	2,993,194	85.7	±1.1	30	U-Pb	U of Arizona, V. Valencia
JLB02	Roncesvalles sandy strata, detrital	228,549	2,994,123	149		100	U-Pb	U of Arizona, V. Valencia
JLB01	sandstone at base of KVAC, detrital	229,222	2,992,035	85		10	U-Pb	U of Arizona, V. Valencia
JL-B9-D1	Dolores Diorite	226,389	2,992,852	54.6	±1.2	11	U-Pb	Boise State, V.Valencia

Batopilas Stratigraphy

The stratigraphic section presented here is based mostly on mapping carried out in 2006 and 2007 by the author. The prior regional mapping by Bagby (1979) did not apply names other than the regional groupings such as lower volcanic sequence (lower volcanic complex of McDowell and Keizer, 1977) and the upper volcanic sequence (upper volcanic supergroup of McDowell and Keizer, 1977) and the plutonic suite which only cuts the lower volcanic sequence. Wilkerson (1983) subdivided his lower volcanic series into the San Jose flow breccias and the Arenal flow breccia and mapped the plutonic suite as beneath an unconformity. Wilkerson divided his plutonic suite into the Pastrana Dacite, the Tahonas granodiorite and the Dolores micro quartz diorite. Wilkerson placed two minor formations above the top of the lower volcanic sequence: the Cinco de Mayo conglomerate and the Casas Colorados flow breccia. This whole sequence was capped by the more than 1,000 m thick Yerbanis Rhyolite Tuffs that are the same as Bagby's upper volcanic sequence.

Current mapping determined that the primary unit in the Batopilas District that Wilkerson (1983) mapped as the Pastrana Dacite is actually a package of laminated to thin bedded turbidite rich marine strata interbedded with two submarine andesitic to dacitic flow domes. The sodic-dominated alteration Wilkerson documented probably resulted from the submarine environment of eruption. Because the striking contrast between the interpretations of Wilkerson's Pastrana Formation and the interpretation presented here, the unit name was changed to avoid confusion. Although this unit correlates with other similar outcrops of the marginal basin such as the Cucurpe Formation (Lawton and others, 2003; Mauel and others, 2011), the informal local name of Batopilas Formation has been chosen for the unit at Batopilas. If it becomes obvious that it is the best locality for defining the Jurassic marginal basin strata, it could be proposed as a formal unit. Its greatest weakness compared to Cucurpe is the lack of Lower and Middle Jurassic strata.

Elsewhere in the district the relationships between most rock units below the Yerbanis welded tuffs have been reinterpreted as well. These reinterpretations require renaming to avoid confusion, but the Dolores Quartz Diorite and Tahonas Granodiorite names of Wilkerson have been retained.

The physical relationships between the various units used in this study are shown in Figure 3.12. These relationships have been observed in this field mapping and exploration drilling carried out during the same time period.

Batopilas Formation (Jb)

The Upper Jurassic Batopilas Formation named for the village of Batopilas makes up over 50% of the outcrop in an area over 7 km east to west and 5 km north to south (Fig. 3.13) and its type locality is defined by two different stratigraphic variations. On the south face of Animas Ridge, above and below the Pastrana Mine, it consists mostly of laminated to thin bedded marine strata (Fig. 3.14) that reflect significant volcanic sources, fossiliferous pelagic mudstone and shale locally rich in belemnites and ammonites, and turbidites locally rich in belemnites, ammonites, nerinia gastropods, coral and bivalves (fossil localities, Fig. 3.15). Basal debris flows to turbidites rich in nerinia and belemnites display a pronounced westerly alignment of these elongate fossils (Fig. 3.16). The nerinia-bearing basal debris flows (Fig. 3.17) also contain bivalves and rounded coral fragments (Fig. 3.18), a suite typical of the contemporaneous Upper Jurassic Zuloaga Formation carbonate platform environment deposited on the continental shelf to the east of Batopilas. Submarine andesitic flow domes and breccias (Fig. 3.12) are interbedded with volcanoclastic debris and fossil-bearing turbidite and pelagic strata in the central part of the district. Belemnites (Fig. 3.19) and ammonites (Fig. 3.20) are widely distributed but are richest in debris flow strata (Fig. 3.21) in the eastern part of the district. In the western half of the district the sediment is rich in volcanically derived laminated coarse sand strata with sparse, mostly broken belemnite fossils. The limited igneous rocks of this part of the formation were observed only as rare dikes. The two stratigraphic variations are separated by a west-southwest vergent thrust also intruded by a sill off of the main Tahonas stock that underlies the village of Batopilas. The sill form of this more altered portion of the stock was determined by earlier exploration drilling by Peñoles and the distribution of the outcrops.

The Batopilas formation comprises what Wilkerson (1983) and Wilkerson and others (1988) mapped as the Pastrana Dacite. However the major oxide chemistry of Wilkerson (1983) on porphyritic phases classifies the submarine volcanism as a variety of andesite by the common chemical classification systems for volcanic rocks. The physical behavior of the flow domes and carapace breccias, is more characteristic of a more silicic magma such as a dacite as used by Wilkerson (1983). Because this unit is dominated by laminated to thin bedded fossiliferous submarine sedimentary rocks (Fig. 3.21), changing the name from the Pastrana Dacite to the Batopilas Formation is appropriate.

Regionally the Batopilas appears to correlate with thin-bedded volcanic-rich marine strata north of the Reforma District, Chihuahua, 45 km to the west (Fig. 3.1). The strata north of Reforma correlates lithologically best with the Batopilas Formation in the west part of the Batopilas District but is less indurated probably as a result of a lack of stocks north of Reforma as found in the Batopilas District. The thin-bedded marine strata in the Moris district, 150 km west northwest of Batopilas (Fig. 3.1) lithologically correlates best with Batopilas Formation in the eastern part of the district. Additionally the Batopilas Formation lithologically correlates with dated fossiliferous shale from southeast of Sahuaripa, Sonora (Fig. 3.1) and the abundant dated outcrops found in the Cucurpe, Sonora region (Fig. 3.1, Villasenor and others, 2005; Mauel and others, 2011). These widely dispersed occurrences are similar enough that they could be given one formal name. Despite using the local name of the Batopilas Formation in this study the completeness and detail of the section studied at Cucurpe (Mauel and others, 2011) would favor the Cucurpe Formation as the best regional name for the Upper Jurassic strata particularly if paleontological confirmation could be obtained. Another option would be to raise Cucurpe to group status and local names such as Batopilas would remain at formation level.

Subdivision of the Batopilas Formation into members is based on sedimentary versus volcanic lithology and stratigraphic position. Although distinctive turbidite strata were observed, they never proved useful in subdividing the sedimentary section that is given the name Roncesvalles Member. Two submarine flow domes were mapped as separate members, the Minas and Animas Members, because mapping and drilling confirmed that they were distinct stacked domes with marine strata separating them.

The Batopilas Formation west of the Roncesvalles fault consists mostly of sedimentary strata similar to the eastern half of the district but with fewer fossils and no observed flows. The sill shaped branch of Tahonas stock near the Roncesvalles fault (Figs. 3.13 and 3.26) is believed to be evidence of a low angle thrust fault separating the two halves of the district.

Minas Member (Jbmv). The Minas Member of the Batopilas Formation consists of submarine flow dome of augite-plagioclase andesite or dacite extruded as a dome with a breccia shell and intensely altered to amphibole-sodic plagioclase-epidote. The Minas is named for the Arroyo de las Minas that drains into the east side of Batopilas, the type locality for the member. As noted above the Roncesvalles Member contains abundant debris from the Minas from coarse recognizable fragments to fine sandy grit particularly adjacent to the domes. Dikes of similar composition and alteration cut these eruptive rocks and continue across the Roncesvalles Member into the Animas Member flow dome (Fig. 3.13). The Minas Member appears to be the oldest outcropping unit. Drilling in the Animas area in the northeast part of the district has penetrated the Minas flow dome and encountered more similar strata at depth (Fig. 3.22). The circular steep sided dome with a carapace of auto-breccia that mixes with the surrounding fossiliferous strata confirms its submarine volcanic origin.

Roncesvalles Member (Jbrs). The Roncesvalles Member of the Batopilas Formation consists mostly of laminated to thin bedded pelagic shale (Fig. 3.14) turbidites and volcanoclastic debris. Ammonites and belemnites are variably dispersed throughout the member (Fig. 3.19 and 3.20) in pelagic shale and calcite-cemented basal debris flows to a turbiditic unit near the lower contact with the Minas Member submarine flow dome. The fossils in the lower Roncesvalles turbidite basal debris flow are clearly transported fragmental fossil hash (gastropods, bivalves and corals, Figure 3.17 and 3.18) with a dominant east-west alignment of elongate fossils (belemnites, Fig. 3.16 and 3.19; and gastropods). The Roncesvalles strata are laminated to layered (1mm to several meters) throughout the district (Fig. 3.14 and 3.23). In diamond drill hole (DDH) BA06-08 (Fig. 3.24) interfingering of volcanic debris and belemnite fossil-bearing shale and mudstone confirms the submarine environment of deposition for the Minas Member below.

A surface sample of rock very similar to the core (Fig. 3.24) was collected for detrital zircon analysis. A focused peak of 149 Ma was obtained from 100 zircons (Fig. 3.25) confirming the local volcanic source of most zircons. Because of the high dilution factor of the local volcanic source, only sparse Grenville, Granite-Rhyolite Province, Yavapai and Archean zircons were detected (See Appendix A).

Animas Member (Jbav). The Animas Member (Fig. 3.22) of the Batopilas Formation consists of submarine volcanic flows of augite-andesite intensely altered to amphibole-sodic plagioclase-epidote. The Animas Member is only distinguishable from the Minas Member by stratigraphic position. On the north side of the district, the principal outcrop of this unit comprises the top of Animas Ridge for which it is named. Drilling confirms that the Roncesvalles member strata do occur below the Animas Member as mapped above the Pastrana Mine (Fig. 3.25). The carapace breccia so prominent over the Minas Dome is absent on the Animas dome. If it did exist, it possibly has been eroded along the angular unconformity found cutting its upper surface.

Batopilas Formation Dikes (Jbd). Batopilas dikes consist of augite-plagioclase granodioritic to felsic dikes that typically are less than 1 m in width and are mostly found within the area of the Minas and Animas domes. The dikes were mostly left unmapped because of narrow widths and lack of contrast between dikes and domes. All of the dikes are altered to propylitic and amphibolitic phases probably related to submarine emplacement. On the north side of the Minas flow dome near the Pastrana Mine, a Jbd dike cuts from the Minas dome through the overlying Roncesvalles strata into the capping Animas flow dome (Fig. 3.13). The concentration of dikes in the dome area further supports the interpretation that these sites are volcanic domes.

Angular Unconformity One.

The upper surface of the Batopilas Formation is an angular unconformity of a minimum of 200m relief separating thrusted and folded marine strata from gently (up to 20°) east-dipping subaerial volcanic rocks.

Late Cretaceous volcanic and intrusive activity.

The Batopilas Formation is unconformably overlain by eastward-dipping subaerial andesite flows and breccias inferred to be the 95 to 85 Ma Tarahumara Formation (McDowell and others, 2001) based on the U-Pb dates of 88 to 85 Ma (see Appendix A and Supplementary Files) from the cross-cutting assumed coeval granodiorite to quartz monzonite stocks. Igneous ages are based on 30 zircons per sample if available.

Tarahumara Volcanic Series (Kav). The volcaniclastic units that comprise most of the east side of the district (Fig. 3.13 and 3.14) consist of greater than 500 m of andesitic flows, flow breccias and lahars with minor dacitic to rhyolitic tuffs. This unit appears to have been deposited in a subaerial environment due to the lack of alteration of the igneous minerals to clays and other low temperature hydrous minerals. The sequence is cut by the Tahonas, Dolores and Las Juntas intrusive rocks and is altered by the Tahonas intrusive rocks. The Tarahumara unit is commonly included within the lower volcanic sequence or complex, but because of the imprecise nature of this name (applied to rocks from Jurassic to Eocene in age), the proper name Tarahumara (Wilson and Rocha, 1949; McDowell and others, 2001) should be preferred if the unit in question meets specific criteria. The Tarahumara has not been dated directly at Batopilas but has been dated in the region near the type locality (McDowell and others, 2001). Observations indicate that the Tarahumara Andesite postdates the Late Cenomanian (95 Ma) major structural shortening that affects the underlying Jurassic sedimentary strata and predates the 88 to 85 Ma intrusive stocks that cut the andesite (Figs. 3.13, 3.28 and 3.29). The Tarahumara displays structurally simple eastward dip and normal faults that indicates a solid correlation with the Tarahumara Formation (type locality near Tonochi, Sonora 280 km to the northwest (Wilson and Rocha, 1949). The main difficulty with the

Tarahumara Formation is that the name is applied to two separate volcanic sequences. In the study by McDowell and others (2001), the lower sequence dates at 90 to 89 Ma by U-Pb; these units are capped by 73 to 70 Ma andesite and dacite volcanic rocks that are cut by the 65 to 55 Ma Laramide stocks.

Tahonas Quartz-monzonite (Tqmp). The quartz-monzonite to granodiorite porphyry dikes and stocks show considerable variation in phenocryst size (up to 1 cm dipyramidal quartz) and quartz content (1 to 10%). These intrusive dikes and stocks occur throughout the pre-Tertiary part of the district. These stocks and dikes could be subdivided into a variety of individual igneous groups based on location and lithologic variation; because of the consistent iron stained argillic alteration and consistent cross cutting relationship with the Tarahumara andesitic flows and Batopilas Formation, they have been grouped together for the purpose of this mapping. The Tahonas quartz-monzonites and quartz latites are classified using the major oxide chemistry of Wilkerson (1983). The sill-like lobe of the Tahonas (Coralitos area) injected into a thrust fault had stronger alteration and metal anomalies than most intrusive bodies and was drill tested by Peñoles. This testing defined the sill form of this body of quartz monzonite.

U-Pb radiometric dating of these stocks and dikes for this study finds that they range in age from 88 to 85 Ma and their close association with Mo mineralization is confirmed by a 84-Ma Re-Os date on molybdenite (see Appendix A Fig. A.1).

Quartz-Latite porphyry (Tqlp). Quartz-latite porphyry dikes and small stocks are associated with the Tahonas quartz monzonites and both phases are typically found together. The dates on the quartz latite porphyry dikes are variable. The oldest date is 86 Ma, consistent with the Tahonas quartz monzonite porphyries. The most anomalous date is on a mostly aphanitic latite cutting the Tahonas in the Coralitos area that dated at 73 Ma, an age otherwise unknown in this area but common in the central Sonoran study by

McDowell and others (2001). The youngest date obtained from a quartz latite porphyry dikes is 28.9±0.5 Ma (see Appendix A) from a branching dike that cuts the Tahonas and Dolores stocks between Coralitos and the Batopilas village (Fig. 3.13). This age links the dike to the Oligocene volcanic rocks capping the region. This dike has a quartz phenocrysts content ranging from 1 to 10% with some distinctive large (to 1cm) dipyramidal quartz phenocryst.

Las Juntas granodiorite (TKjgd). The Las Juntas Granodiorite is a medium to fine grained granodiorite. Mineralization is not known to occur in the immediate vicinity of this unit. Its age relation with other intrusive systems is unknown, but it does cut the Tarahumara Formation.

Post Tarahumara Unconformity.

A moderate angular unconformity separates the Tarahumara volcanic strata from the overlaying Eocene and Oligocene volcanic rocks.

Eocene Igneous Suite

The Eocene part of the section consists of a regional sheet of rhyodacite flows, the Satevo Rhyodacite and the Dolores Quartz Diorite.

Dolores Diorite (Tdd). The Dolores Diorite (named by Wilkerson, 1983) is a dark gray fine-grained quartz diorite with biotite as the principal mafic mineral. The Dolores exhibits many perplexing features. The cross-cutting relationships between the Dolores and Tahonas intrusive rocks have sometimes been confusing; but now three radiometric ages have consistently placed the Dolores as Eocene including a Rb/Sr date of 50 Ma (Bagby, 1979), a K-Ar date reported by Wilkerson and others (1988) of 51.6±1.1 Ma, and an U-Pb date of 54.6±1.2 Ma (this study) whereas Tahonas-type igneous rocks have been dated eight times in this study at 88 to 85Ma (see Appendix A and map Fig. A-1). The

Eocene Dolores was emplaced about 8 million years prior to the Satevo Rhyodacite eruption. If there was an extrusive phase of the Dolores Diorite it appears to have been stripped away by intervening erosion.

Tertiary Angular Unconformity

The Dolores, Tahonas, Tarahumara and older rocks are truncated by an Early Cenozoic angular unconformity of moderate relief and more than 100 meters accumulation of sandstones and conglomerates in the southeast corner of the map area. Detrital zircon dates from a sandstone contained within this horizon yields a 6 zircon peak of 83 to 88 Ma, consistent with Tarahumara and Tahonas igneous rocks, while single zircon dates of 73, 134, 149, and 227 Ma (see Appendix A, sample JLB-01) are Triassic through Late Cretaceous ages. The paucity of zircons from this sandstone was surprising, but all results were consistent with known geology except for the one Triassic zircon. The data on detrital zircons from the Roncesvalles Member of the Batopilas did contain a Triassic zircon and is a possible source of this Triassic zircon.

Satevo Rhyodacite (Tsd). The Satevo Dacite sits atop the aforementioned angular unconformity which cuts the Dolores Quartz Diorite, the quartz monzonitic series of igneous rocks and all older rocks. The name Satevo Rhyodacite for the village and mineral district south of Batopilas is used here as a field term. Satevo Rhyodacite consists of flow-dome complex with lateral flows and flow breccias. The Satevo Rhyodacite resulted from an Eocene eruption dated for this study at 47 Ma by U-Pb on 30 zircons (see Appendix A map Fig. A.1). The unit contains barite-calcite-galena veins at the Transito Mine on the west side of the district and calcite-sphalerite-galena veins at Satevo. The Satevo flow is also cut by Au-quartz veins at Satevo, with all observed veins appearing to predate the Yerbanis tuffs. The Au-producing Cerro Colorado dome was not mapped as part of this project, but samples indicate it is petrographically similar to the Satevo rhyodacite. The age difference (Satevo 47 Ma and Yerbanis 32 Ma from Bagby, 1979) indicates a hiatus in deposition, but no significant unconformity can be documented where mapped. The Satevo Rhyodacite appears to have been included in the Yerbanis Tuff sequence by Wilkerson (1983).

Oligocene tuffs, flows and intrusive rocks

The Oligocene section in the Batopilas quadrangle was mapped and dated (see below) by Bagby (1979), who referred to this section as the upper volcanic sequence. Wilkerson and others (1988) referred to this as the Yerbanis Formation. Greater detail has been added only at the base of the section in this study.

Yerbanis Tuffs and Flows (Tyrt). The Yerbanis Formation named by Wilkerson (1983) makes up the thick package of Oligocene rhyolite welded tuffs, rhyolite flow domes and lesser intermediate to mafic flows which caps the stratigraphic section. Yerbanis rhyolite flows and tuffs were called the upper volcanic sequence by Bagby (1979) and dated as 32 to 28 Ma (Oligocene). They cover the NW section of the map area and appear to postdate mineralization.

Vent Breccia (Tysb). The Batopilas Formation is extensively brecciated underneath Yerbanis tuffs, possibly by pre-caldera gaseous venting. The venting appears to have happened prior to the tuff eruption because mixing of the breccia with the tuff was not observed. The pebble dikes increase in intensity toward the vent breccia lending further credence to the caldera-venting model.

Flow banded rhyolite (Tfbr). A 250-m wide flow banded rhyolite dike occurs in the upper reaches of Arroyo Camuchin 4 km west of Batopilas. This dike feeds a rhyolite flow dome in the lower part of the Yerbanis tuff sequence which was not mapped.

Miocene volcanic rocks

Miocene volcanism is represented only by basaltic-andesite dikes in the Batopilas district.

Basaltic Andesite Dikes (Tba.) Basaltic andesite dikes cut the complete section of the district including the Yerbanis Tuffs. They are encountered in the mines as well as on the surface. Basaltic-andesite dikes are dark gray to black, fine-grained magnetic dikes from 0.3m to 3m wide. The basaltic andesite dikes were observed cutting the Yerbanis Rhyolitic Tuffs at San Jose on the drainage divide on the western limit of the map and are believed to be feeders to Miocene volcanic rocks mapped and dated by Bagby (1979) at 20.7±0.3Ma (K-Ar whole rock). From this relationship they are believed to postdate mineralization. They generally trend northerly but do tend to follow earlier structures such as the more northerly stretches of the older ring structures.

Quaternary Alluvium and Landslides (Qal and Qls)

Quaternary alluvium covers bed rock generally only a few meters thick except along the Batopilas River. Because of this and the reconnaissance nature of the mapping, it is generally ignored except along the river. Landslide material off of the high cliffs of the Yerbanis Tuffs occur on Animas Ridge on the north side of the Batopilas District and continue north along the cliff face to the north out of the mapped area. These units were mapped as the pre-Yerbanis units named Casas Coloradas and Cinco de Mayo Conglomerate by Wilkerson (1983).

Batopilas Structure

Structural features mapped in the Batopilas area range from thrusting and folding in the older Batopilas marine and volcanic strata through ring and radial fractures derived from doming and subsequent volcanic collapse along the doming derived ring structures.

The latest prominent structures are north-trending normal faulting reflecting Miocene extension.

The Jurassic Batopilas Formation reflects a shortening environment with thrusts, fault-bend folds and folds that appear to only affect the strata of this unit (Fig. 3.27). This would imply that there was a shortening event that was a precursor to the overlying subaerial andesitic volcanic rocks which only have normal faults cutting such deformation. Differences in structural competence between these units could explain the difference, but regional correlations with the Tarahumara andesite are found always resting on deformed Bisbee Group strata and argues against such an interpretation (McDowell and others, 2001). The principal axes of folding range from NNW to WNW with overall plunges to the SE. The fault-bend fold mapped in the pelagic shale of the Roncesvalles Member between the two identified submarine volcanic domes (see unit descriptions) of the Minas and Animas Members of the Batopilas Formation and less well defined fault-bend folds (less well exposed) in the western part of the district indicate westward-directed thrusting. Exploration drilling in the Corralitos area southwest of the main Batopilas district drilled through the outcropping stock into underlying Batopilas Formation. This feature is now interpreted as a sill projecting out of the Tahonas stock following a preexisting east-dipping thrust fault within the sedimentary strata.

The timing of shortening deformation at Batopilas, as determined locally, can only be limited between the Late Jurassic Batopilas and the Early-Late Cretaceous of the Tarahumara because of the lack of any strata recognized as Lower Cretaceous. Tight folding 45 km to the west of Batopilas in the Reforma area in Albian limestone unconformably overlain by unfolded clastic strata suggests that the folding event may have occurred between the Middle Cretaceous and Mid-Late Cretaceous. The documentation of Late Cenomanian folding and thrusting involving known Jurassic marine strata at Sahuaripa 265 km north-northeast and in the Chanate Mountains 580 km northwest in northwest Sonora indicate that the most likely age of shortening of these Jurassic strata is late Cenomanian.

The contact of the Minas Dome with the overlying Roncesvalles Member suggests a carapace breccia formed on the crest and flanks of the dome, separating the central Minas Member and surrounding Roncesvalles Member strata of the Batopilas Formation. These breccias are found most prominently on the northwest flank of the dome (Fig. 3.29) and are found to have Minas fragments in beds with belemnite fragments within the Roncesvalles off of the flanks of the dome. This interpretation is consistent with carapace breccias observed along the flanks of active volcanic domes shedding volcanic debris onto their flanks.

Moderate to gentle regional tilting characterizes the Tarahumara Formation, the same as in its type locality 280 km to the northwest (McDowell and others, 2001). Eastward dips typically are less than 20° and about 10° on average.

Silver-bearing veins and quartz monzonite-latite intrusions both exhibit a radial distribution around the north edge of the Minas volcanic complex (Fig. 3.13). This suggest doming over a blind intrusion in this area. This radial pattern rotates into a dominant N45°E trend of veins on a district scale. The N45°E orientation probably represents the direction of maximum principal stress at the time of intrusion and mineralization. Deviations from the N45°E direction appear influenced by the rise of an underlying magma as illustrated by the increasing numbers and in width of dikes with greater depth of exposure in the deep canyons. The near radial pattern is observed in the Roncesvalles-Pastrana-San Pedro-Vacas-Cobriza-Acendrada vein set (Fig. 3.13). Structurally the similarity of the 88-85Ma dikes and the veins suggest near contemporaneous emplacement.

Ring structures related to the Oligocene Yerbanis Tuffs appear to cut through the district. They can be observed dropping the Yerbanis down against the Jurassic Batopilas on Animas Ridge where the road crosses over into the Yerbanis.

The youngest documented faulting event is a NNW-trending normal fault that down drops the Laramide volcanic rocks against the Jurassic section. A small outlier of the Tarahumara on the up-thrown side is exposed on the southeast end of Animas Ridge (Figs. 3.13 and 3.30).

Batopilas Mineralization

The Batopilas Silver District is principally known for its unusual rich hypogene native Ag veins hosted mostly in calcite gangue with accessory quartz gangue. Economically minor values of galena and sphalerite are found zoned in the same veins. Recent activity in the district consists mostly of placer mining for silver and small scale gambusino mining of galena from Ag poor upper zones above the Ag rich zones of the Pastrana, Santa Domingo and other veins in the district (Fig. 3.28).

Dispersed non-economic occurrences of molybdenite are found in the district particularly at Corralitos (2 km west of Batopilas, Fig. 3.28) and in the Porfirio Diaz Level of the Todos Santos vein (Fig. 3.29). The molybdenite is hosted in quartz veins cutting quartz monzonite stocks and dikes.

Only trace amounts of Au are known in the immediate district, all distal to the stock cut by the San Miguel and Santo Domingo veins (labeled Au in Fig. 3.29). Two quartz veins occur on the northeast projection of the Santo Domingo vein. Close to one ppm Au can be detected over a 1 to 2 cm wide sample of these narrow quartz-pyrite veins.

The native silver veins are found cutting all three members of the Batopilas Formation; the Minas, the Roncesvalles and the Animas Members. The Minas Member hosts a significant portion of the Batopilas District silver vein mineralization in the center of the district. The Pastrana Mine is not the cluster of Roncesvalles-San Roberto-Todos Santos veins as reported by Wilkerson and others, 1988 but the Pastrana Mine as indicated by claim maps (e.g. Brodie, 1909 and field observations) is located immediately north of the Roncesvalles-San Roberto-Todos Santos vein system. Stopes of the Pastrana vein are mostly in the upper Minas Member but also continues into the Roncesvalles and Animas Members. The Pastrana Vein mostly cuts the Minas Member as does its southern extension the Escritorio Vein. At the surface the Roncesvalles, Todos Santos and San Roberto Veins are all in the Roncesvalles Member, but in the Porfirio Diaz Level they are mostly in the Minas Member. In the Porfirio Díaz Level the hanging wall of the Roncesvalles vein is the Roncesvalles Member, but post-mineralization displacement on the Roncesvalles fault may place it in this position. In the Animas Mine area the mineralization is in the Animas Member at the surface, but it is not known if veins continue into the Roncesvalles and Minas Members at depth. In the western part of the district the Roncesvalles Member is the principal host to the east northeast-trending veins.

Around the San Miguel stock most mineralization is exposed cutting the Tarahumara Formation, but some vein exposures and underground workings occur in the stock and the Roncesvalles Member of the Batopilas Formation. This is consistent with the several small outcrops of Roncesvalles Member in the area (Fig. 3.29)

In addition to these major rock type associations, quartz latite dikes crop out along the vein contacts of many veins including the Animas, the Tescalama, the Cobriza, the Vacas and the San Pedro to name a few (Figs. 3.28 and 3.29). While not observed on the surface, the quartz latite dikes form hanging wall or footwall rocks to the San Roberto and Todos Santos veins at the Porfirio Diaz Level.

Batopilas District Zoning

Wilkerson (1983) proposed that the native silver veins of Batopilas displayed a zoned silver pattern peripheral to the north side of the Tahonas phase of the quartz monzonitic intrusive system. Mapping during this phase of the Batopilas project repeatedly encountered a close spatial relationship between mineralization and dikes of this intrusive phase including quartz latite dikes of the same age.

The most common vein assemblage found in the Batopilas District is native silver in white calcite gangue with subordinate values of galena and sphalerite. This assemblage is observed in most veins of the district but with decreasing amounts of Pb and Zn sulfides in the western part of the district and in the Animas area to the northeast (Fig. 3.29). This assemblage is known to continue for at least 520 m vertically (from 580 m elevation, 22 m below the Porfirio Diaz Level, to 1,100 m elevation in the uppermost part of the Pastrana Vein). Elevations are reported as above mean sea level.

In the upper 10 to 30 m of some veins (possibly a product of non-erosion), galena in white calcite gangue is found with only geochemically detectible amounts of silver. Observed localities include the uppermost part of the Pastrana Vein (approximately 1,100 m to 1,130 m elevation along the vein) where it cuts into the overlying Animas Member flow dome and the northeastern most stopes of the Santo Domingo Vein (between 770 to 800 m elevation). A number of other occurrences are reported by local gambusinos (operators of small mining operations) at scattered locations around the periphery of the San Miguel and Santo Domingo Vein systems at upper levels of the various veins.

Sparse quartz gangue appears irregularly dispersed throughout the district with several major exceptions. The Cobriza Vein, that appears to be a southwestern extension of the Animas Vein system, is dominated by quartz gangue speckled by copper oxides on its surface exposures. Workings along the Cobriza quartz vein exposed white calcite veins with native silver as a second vein immediately adjacent to the quartz vein. The southwestern-most exposures of the Cobriza Vein displayed calcite seams in the massive quartz gangue that contained native silver. The north northeastern most extension of the Santo Domingo vein system (on strike with the Santo Domingo vein) consisted of two outcrops of pyritic quartz veins with anomalous Au values (labeled Au in Fig.3.29). The first lies on the ridge above the stopes in the galena-calcite zoned veins and the second, the most distal, lies in the drainage north of the ridge.

Acanthite and sulfosalts of silver (proustite and pyrargyrite) are scattered throughout the district in minor amounts. Small but notable crystals are found in various collections (Wilson and Panczner, 1986) but well documented distribution data is lacking. The most significant occurrences of acanthite are reported from the Animas area mines where it was observed during this study. The San Miguel-Santo Domingo system in the southeast part of the district is where most samples of proustite-pyrargyrite sulfosalts crystals are reported. Barite was recognized as a peripheral mineral species during this study in the Animas area veins and in the westernmost mine of the district, the Triumfo Mine.

Age and origin of Mineralization.

Dating of the mineralization event has proven challenging. Many physical relationships such as Ag veins along quartz monzonite and quartz latite 85 to 88 Ma Tahonas age dike contacts and the Roncesvalles Vein terminating against the Dolores stock suggest a relationship between the Tahonas intrusions and the Ag mineralization (Wilkerson and others, 1988). The small calcite galena veinlets observed in the Dolores suggest a silver mineralization age that postdates the Dolores. U-Pb dating of zircons in various dikes attempted to constrain the timing of the mineralization. The majority of dating was done on the Tahonas family of quartz monzonite stocks and dikes and quartz latite dikes spatially associated with Ag mineralization. The eight resulting ages ranged from 88 to 85 Ma (Appendix A, map Fig. A-1). Wilkerson and others (1988) considered the Tahonas as the youngest major intrusion in the district, but dating indicates that the Dolores is 30 Ma younger than the Tahonas quartz monzonite igneous system. Dating on the Dolores began with Bagby (1979), obtaining a date of 50 Ma by Rb/Sr. A K-Ar date on biotite from the diorite of 51.6 Ma was reported by Wilkerson and others (1988). U-Pb dates on zircons from the Dolores Diorite collected for this study obtained an age of 54.6 ±1 from 11 zircons.

The relation between mineralization and the Dolores quartz diorite is still unclear. The Dolores appears to be either a poor host for mineralization or post-mineral because of the apparent termination of the main veins at the Dolores stock contact (Fig. 3.13). At the Dolores and Caballo Mines narrow native silver-bearing calcite veins appear to cut the Dolores, but at both localities extensive brecciation suggests the suspension that the mineralized rock may be roof pendants contained in the Dolores. Between the Dolores and Caballo Mine small calcite galena veins were observed. The Roncesvalles, San Roberto and Todos Santos veins all terminate at their contact with the Dolores at the southwest ends of the veins in both the Porfirio Diaz and Peñasquito levels of the veins. The veins of the San Miguel-Santo Domingo system also terminate against Dolores Diorite at their southwest ends as well as the Nevada mine at its northeast end. The projections of the various veins across the Dolores were observed in the field with no veining, structure or alteration encountered except for minor epidote veins south of the Escritorio Vein (Fig. 3.29).

The most important occurrence for dating mineralization occurs along the Roncesvalles vein on the Porfirio Díaz Tunnel level. It consists of an unusual breccia within the vein that has been considered in the past to be a post vein fault breccia in which economic grades of fragments of banded native silver-calcite were produced by faulting. A quartzdiorite porphyry appears to have been still partially molten when injected into the Roncesvalles Vein. These fragments display rounded amoebic irregular lobes branching in all directions that appear to have been deformed by the wall rock fragments surrounding them (Fig. 3.30). Banded calcite-Ag vein fragments mixed with the quartzdiorite blobs and the banding of the mineralization fragments sometimes terminated against the irregular fragments of quartzdiorite (Fig. 3.31). This breccia was recognized as a distinct ore body in 1900 era mining maps. These amoeba form breccia dike fragments were determined to be 54.9±0.8 Ma from U-Pb ages from 33 zircons (this study, see Appendix A and map Fig. A.1) within the range of expected variation between a U-Pb age and the prior K-Ar age on the Dolores Diorite. This dating indicated that the major veins were in place at the time of emplacement of the Dolores Diorite.

Un-brecciated quartz latite dikes occur along the Todos Santos and San Roberto veins, both major foot wall veins to the Roncesvalles vein. In the wall of the Todos Santos vein, quartz latite cuts the quartz monzonite dike. Surface exposures of the dikes are more limited but were found south of the old Roncesvalles surface workings in what is probably named the Arroyo Roncesvalles and along the Roncesvalles vein north of the projection to the surface of the Porfirio Diaz Tunnel.

One episode of mineralization that proved to be directly datable was the molybdenite. A Re-Os date on the molybdenite near the Todos Santos-San Roberto vein intersection yielded 84.4±0.4 Ma (Sample JL-B9-M1A on map Fig. A.1), essentially the same as the Tahonas stocks. It is difficult to determine what if any relationship the quartz-molybdenite might have with the silver-calcite mineralization since the quartz-molybdenite forms at much higher temperatures than the silver-calcite (Wilkerson and others, 1988). Calcite-silver veins were recognized cutting the quartz-molybdenite veins near the junction of the Todos Santos and San Roberto veins on the Porfirio Diaz Level.

Observations of Delores age igneous rock cutting silver-calcite mineralization and calcite-galena veinlets cutting the Delores Quartzdiorite suggest that there may have been two episodes of silver-calcite veining. Kallstrom (2012) concluded, based on sulfur lead and strontium isotope studies, that marine brines circulating in basement rocks may be the source of the unusual fluids that deposited these atypical native silver-calcite veins. Repeated episodes of similar mineralization are considered unlikely but not impossible, as observed at Jurassic and Laramide Cu porphyry deposits in Arizona. A second episode of native silver mineralization in calcite or reactivation may be more likely if Kallstom's model of a marine sedimentary basin brine origin of ore fluids is correct. Lyons (2008) presented indirect evidence, particularly spatial correlation between mineralization and the basin and the Jurassic basin chemistry may have had a profound influence on metal distribution in the region.

LLUVIA DEL ORO DISTRICT, CHIHUAHUA

The Lluvia del Oro Gold District is located in southwestern Chihuahua 32 km east of junction of Sonora-Sinaloa and Chihuahua, 6 km east of the Reforma, Chihuahua Ag-Zn district and 37 km west-southwest of the Batopilas District, Chihuahua. Geologically the district consists of a synclinal sequence (oldest to youngest) of reworked fluvial shale and sandstone; limestone, marl and rudistid reef limestone; all capped with another reworked fluvial sandstone (Fig. 3.32). This lithologic sequence is a very close match to the Bisbee Group of northern Sonora (Dickinson and others, 1989; Lawton and Olmstead, 1995; Rosales-D. and others, 1995; and regional observations made during this study). A major high relief angular unconformity cuts the folded strata with karst development in the limestone below the unconformity. Regionally hundreds of meters of relief are exposed on this unconformity with limestone outcrops appearing to have formed the high peaks in the form of north to north northeast-trending ridges on this paleosurface. This rugged topography was buried in part by conglomeritic sandstone, followed by a thick outpouring of andesite flows from local vents that show limited deformation and tentatively correlated with the Tarahumara Formation (discussed in Batopilas stratigraphy). This andesite is capped with Eocene and Oligocene dacitic to rhyolitic volcanic eruptive strata of the Sierra Madre Occidental Volcanic Field along a less dramatic angular unconformity.

Six kilometers west of Lluvia del Oro, another north northeast-trending folded ridge of assumed Albian-Aptian limestone bounded by clastic strata hosts the Reforma, Chihuahua mineral district. North of Reforma the limestone ridge ends at a thrust contact over volcanic debris rich strata that is lithologically identical with the Upper Jurassic Roncesvalles Member of the Batopilas Formation and the Upper Jurassic strata of the Moris area. No reported paleontological ages were encountered in the literature, just lithologic correlations. The Lower Cretaceous strata was clearly strongly folded when thrust over the weakly deformed underlying Upper Jurassic strata.

No direct dating was carried out in the Lluvia del Oro District, but lithologic and structural similarities allow correlation of the folded strata at Lluvia del Oro with the folded strata of Zataque District, Sonora-Sinaloa as well as Reforma, Chihuahua. The limestone-marl-limestone sequence at Zataque is underlain by shale, sandstone and tuff as at Lluvia del Oro. Tuffaceous beds found in the clastic strata below the limestone and marl sequence at Zataque are similar to those encountered in the Morita Formation (Gonzales-L. and others, 2000) north of Arizpe, Sonora. Because of their similarities, these tuffs from both Zataque and Arizpe were sampled and dated. An age of 138 Ma was obtained from detrital zircons (see Appendix A, Samples JL-MO-02) from the tuffaceous unit stratigraphically beneath the limestone-marl-limestone sequence at Zataque in the core of the anticline. The tuffaceous strata sample from Arizpe yielded a 124 Ma U-Pb detrital zircon date (Appendix A, samples JL-AS-01 and 02). While displaying a 12 Ma spread in age, both of these dates are consistent with the Alisitos Arc inferred to be located west of Zataque and Arizpe in what is now Baja California (Dickinson and others, 1989). These two dates and the lithologic correlation with the Bisbee Group of northern Sonora further support the correlation between the overlying Mural Formation of the Bisbee Group of north central Sonora and the folded limestone and marl strata both at Zataque and Lluvia del Oro. The limestone occurrences are part of a series of limestone, marl and sandstone outcrops that when not extensively metamorphosed by the Sonora-Sinaloa Batholith display a sequence of strata identical to the Morita-Mural-Cintura Formations of the Bisbee Group in northern Sonora. The folding is interpreted to be the result of overthrusting of the Bisbee equivalent strata over the Jurassic marginal basin. The overthrust relationship is recognized from the variability of the strata found exposed beneath the Bisbee equivalent strata. At Gochico, Sonora Lower Cretaceous slope strata underlies the Bisbee equivalents, but at Reforma, Chihuahua (6 km west of Lluvia del Oro) the Jurassic basin fill strata directly underlies the folded strata.

Previous work

The Lluvia de Oro Mine occurs as silica replacement in limestone that lithologically correlates with the Mural Limestone of the Lower Cretaceous Bisbee Group as observed in this study at the Montana del Oro Prospect, 38 km WSW of Lluvia del Oro. CRM (Consejo Recursos Minerales) mapped and drilled around the old gold mines. The best reports on CRM exploration results are unpublished reports including an anonymous report of May, 1986 and a CRM report by Aparicio-Cordero (1988) which contains their drilling results, a geologic map and cross-sections. The property was explored again by Minas de San Luis (Luismin) during the mid-1990's, but their unpublished final report only mentioned the number of drill holes (5) and total meters (778m).

SGM geology maps cover the area with the Huatabampo G12-6 1:250,000 scale map (Escamilla Torres and others, 2000), and the Tasajeras G12-B59 (Aparicio-Cordero and Escamilla-Torres, 2004) and the Cieneguita Lluvia del Oro G12-B49 (Gymsa S.A. de C.V., 2008) quadrangles at a scale of 1:50,000.

Lluvia del Oro Regional Stratigraphy

The earlier published maps (Escamilla Torres and others, 2000; Aparicio Cordero and Escamilla Torres, 2004) include all strata older than Tertiary volcanic strata in one unit while the newest map (Gymsa, 2008) subdivides the pre-Tertiary strata into more units. Recognizable Jurassic strata were not observed in the immediate Lluvia del Oro map area with the closest locality being north of Reforma approximately 8 km west-northwest of Lluvia del Oro. At 1:50,000 scale the limestone at Lluvia del Oro and Reforma is only represented by simple outlines of the approximate location of limestone outcrops within the map unit that includes Jurassic and Lower Cretaceous volcanic, shale, clastic and limestone strata. The andesitic and volcaniclastic strata included in the

Jurassic and Lower Cretaceous unit of the SGM maps are regionally correlated in this study with the mid-Late Cretaceous Tarahumara Formation of central Sonora, based the major angular unconformity separating the Bisbee equivalent strata and the Tarahumara strata. This unconformity was documented on the basis of U-Pb dates on detrital zircons found within this unit north of Zataque, Sinaloa and at Batopilas (Appendix A). Extensive folding below the unconformity and complete lack of folding above it helps distinguish it in the field.

Jurassic Marine Strata. The oldest units encountered in the region appear to be Jurassic marine strata, lithologically similar to those observed in the west part of the Batopilas District in the Batopilas Formation. Undeformed thin-bedded to laminated shales and volcanoclastic sandstone make up most of the marine strata exposed. They are well exposed along the road from Reforma to Creel before climbing up to the volcanic plateau of the SMOVP in the La Guachara area, north of Reforma. No detailed studies are known in the area but mining companies have been actively exploring in the region.

Lower Cretaceous Strata. The limestones in the area have been interpreted as Late Cretaceous. This study has reinterpreted the stratigraphy at Lluvia del Oro and identifies it as Lower Cretaceous based on lithologic similarity with Bisbee Group of northern Sonora and an U-Pb radiometric date of ~138 Ma on a tuff found stratigraphically beneath the correlated limestone at Zataque, Sinaloa (Fig. 3.32 and 3.33). The Morita (Kbmr) equivalent clastic strata contains the dated tuff and is capped by a Mural (Kbm) equivalent limestone and shale that is capped by a Cintura (Kbc) equivalent clastic strata. The Mural equivalent limestone is divided into the lower limestone member (Kbml), the middle calcareous shale member (Kbmm, Figure 3.34) and the upper limestone member (Kbmu).

Upper Cretaceous Strata. The draping of Late Cretaceous andesitic volcanic units (Kut) over a rugged Late Cretaceous paleotopography appears to have led to the CRM misinterpretation of a Late Cretaceous age for the strata. This rugged paleotopography andesite flows and debris which fill paleo-canyons give the appearance that they are older than the limestone and siliciclastic strata which formed the peaks. The limestone commonly displays an irregular rounded weathered surface with karsts filled with clastic debris and andesite. The regional outcrops (occurrences at Zataque to be discussed later) of a nearly identical sequence of fossiliferous (rudisted patch reefs) limestone beds separated by a calcareous shale are capped and underlain by a thick conglomerate-sandstone-shale section now documented to be Lower Cretaceous, correlative with the well-known Bisbee Group of the Lower Cretaceous.

Locally, coarse clastic strata (Late Cretaceous) with limestone clasts separate the andesite from the Bisbee Group equivalent strata. These clastic strata would be equivalent to some element of the Ft. Crittindon-Cabullona Formation of northern Sonora. The andesitic volcanic rocks appear to be closer to vent phases than the more distal bedded units observed 40 km to the east in Batopilas.

The overlying section consist of Lower Cretaceous strata (documented by U-Pb dates on an included tuff at Zataque) throughout the region, from Montana del Oro across to Reforma and the Lluvia de Oro properties (occurrences at Zataque to be discussed). How far the Bisbee Group equivalents continue to the north is still unknown.

Igneous Rocks.

Eruptive material comprises most of the exposures surrounding the district and consists of Late Cretaceous andesite flows and tuffs and Mid Tertiary rhyolite flows and welded tuffs. Intrusive rocks are aerially the least important rock type but appear to most important for district mineralization.

Eocene rhyodacite dikes.

The most important intrusive rocks in the area are rhyodacite dikes, named here the Lluvia Dacite (Tld), for its apparent importance to gold mineralization. These dikes physically appear to correlate with the Eocene Satevo dacite of Batopilas. The fact that these dikes are quartz veined and show close spatial association with mineralization is interpreted to show a causal relationship between these igneous rocks and the mineralization.

Diorite Dikes.

Diorite dikes (TKdi) are exposed along road cuts in the southern part of the area and andesite and rhyolite dikes (Tri) and eruptive flow domes (Trft) are found scattered throughout the region. Based on regional mapping the dikes could be Late Cretaceous through Eocene in age.

Andesitic flows and Tuffs.

The extensive andesitic volcanic field consists of flows lithic tuffs and epiclastic material. This sequence covers the unconformity on the surface of the Lower Cretaceous correlative sandstones, limestones and shales. Its stratigraphic position and the fact that it is being cross-cut by dioritic to monzonitic stocks strongly indicates a correlation with the Tarahumara volcanic strata observed in Batopilas.

Rhyolitic Extrusive Rocks.

The rhyolitic flows and welded tuffs crop out along the west side of the district and petrographically and structurally correlate with the Mid-Tertiary Sierra Madre

Volcanic Province. This exposure appears to be an outlier of the main volcanic field found to the north and east of the Lluvia del Oro District.

Lluvia del Oro Structure

The prominent mineralized structure of the district is a system of N50°E set of faults. These structures control most mineralized veins with the principal exception being the Matilde vein which was tested by drill holes 3 and 4 of CRM. The main N50°E fault appears to be a complex graben with two dacite dikes and the Chivo Vein system. It appears to bound the Cuauhtémoc ore manto on the south side.

Limited exposure prevents confirming whether folding or faulting is the controlling mechanism in the overall district, as faulting is clearly observed in Montaña del Oro. Folding appears important in the Cuauhtémoc ore body. CRM geologists recognized a synform north of the strong multiple fault N50°E zone which host the Chivo Vein and two rhyodacite dikes. This particular synform could be a fold with the faults being axial plane faults or a fault bend fold along the fault zone.

Lluvia del Oro Mineralization

The mineralization appears to be intimately associated with the possible Eocene rhyodacite dikes. Quartz veins (Chiva Vein) and stockworks are observed cutting these dikes and the dikes within the strongest part of the mineral system.

The weathered karsted surface of the limestone appears to be an important control of ore distribution in the Lluvia de Oro-Cuauhtémoc system. The Cuauhtémoc ore body is principally a vertical fracture-controlled solution cavity along a N50°E structure. Travertine deposits still remain in parts of the cavity. The strongest ore development encountered in the cavernous workings occurs closer to the paleosurface at the mine entrance. The Lluvia de Oro Deposit occurs in the upper limestone bed of the Bisbee Group Mural Formation.

The syncline is well exposed out on the west side of the Lluvia de Oro ridge but was hidden by a dense growth of vegetation and buried under landslide debris on the east side near the Lluvia stope. The only apparent explanation is an unmapped northwest-trending fault that hides the exposures. It is possible that this is the reason no mining activity is known on the lower limestone bed.

ZATAQUE (MONTAÑA DEL ORO), SONORA-SINALOA

The Zataque (Montaña del Oro Project) district consists of widely scattered prospects where gold is the primary metal of interest. It is located 25km northwest of Choix, Sinaloa along the Sonora-Sinaloa border. By road Zataque is 20km by pavement to the Huites Reservoir Dam, followed by 8km of improved dirt road to Agua Caliente de Baca and finally 12km of dirt road to Zataque on the southeast corner of the map area. The main purpose of the study in the Zataque area was to provide a geologic framework for exploration efforts in the district.

Previous work

The published maps for the Zataque area consist of SGM maps Huatabampo G12-6 1:250,000 scale map (Escamilla Torres and others, 2000) and the Baca G12-B58 1:50,000 scale map (Quevado Leon and others, 2009). Various unpublished company reports and maps also exist. None of the maps reviewed recognized the physical relationships between the various map units and lumped the units into broad groups that had little use. Quevado Leon and others (2009) lumped all Lower and Upper Cretaceous units together other than the Sonora-Sinaloa Batholith. They recognized that there were limestones in the unit but did not map them separately.

Geologic Setting

The Zataque area lies in a narrow belt of exposure along the north edge of a large lobe of the Sonora-Sinaloa Batholith that cuts the section on the south side and the extensive Oligocene volcanic cover of the Sierra Madre Occidental Volcanic Province to the north. Twelve kilometers north-northwest of Zataque in the Gochico Mine area (Rosas, 1991), a thick section of deep water shelf deposits of moderate to thin bedded limestone interbedded (one third of section) with laminated calcareous shale dominating the outcrop. This section lithologically correlates with Lower Cretaceous strata found during this study in the Chirimoyo, Durango and documented Lower Cretaceous in the Mezcalera overthrust (Prian and others, 2000; Mungia and others, 1998).

Zataque Stratigraphy

The exposed stratigraphy in the Montaña del Oro District consists of folded Lower Cretaceous Bisbee Group age strata at the base cut by a high relief angular unconformity. Coarse conglomeritic clastic strata cover the unconformity followed by early Late Cretaceous hornblende feldspar andesite flows regionally correlated with the Tarahumara Formation of central Sonora. The entire section is capped by Tertiary dacite and andesite flows and rhyolite tuffs (Fig. 3.6.).

Lower Cretaceous. Initially the correlation of the reworked deltaic marine sandstone and carbonate strata with the Bisbee Group Morita, Mural and Cintura Formations of lower Cretaceous age is derived from the stratigraphic sequence and initial correlations of recrystallized fossils as being the size and shape of rudist common in the Mural Limestone. Part of the important stratigraphic character correlating this unit with the Mural Limestone is the marl interval separating an upper and lower limestone, representing a reef to back reef to reef sequence.

Beneath the limestones northeast of the village of Zataque, a tuffaceous bed was sampled from an interval of shale in the core of an anticline in what is interpreted as Mural Formation over the sampled Morita Formation. This unit was sampled (Fig.3.35 southeast corner) and dated at 138 Ma by U-Pb, with a peak of 137 Ma on 19 out of 100 zircons (see sample JL-MO-01 in Appendix A and in Supplemental data). The age range of 131 through 145 Ma for 90 out of 100 zircons, is compatible with the Alisitos Arc proposed to be situated to the west of the region at this time (Dickinson and others, 1989) and now located in the rifted Baja California.

Upper Cretaceous. The Upper Cretaceous volcanic rocks consist principally of andesite flows, breccias lahars and reworked volcanic debris with some dacitic flows and are a potential source area for the Late Cretaceous andesitic debris flows observed 80km west in the Batopilas District. Their 10° northeast dip is consistent with dips observed in the Tarahumara Formation at Batopilas. A sample of reworked volcanic debris from the northwest part of the map area (Fig. 3.35) was collected for detrital zircon dating. The main peak is at 80 Ma with 63/100 zircons between 75 and 84 Ma (Upper Tarahumara) and the second largest peak 23/100 is 151 Ma or Jurassic with 18/100 being Late Jurassic. Twelve zircons with ages between 99 to 143 Ma or Lower Cretaceous came from the Alisitos Arc. In addition there are four Triassic zircons and five Paleozoic zircons. The zircons represent what would be expected during the Late Tarahumara after the major Cenomanian Tectonic event exposed the marginal basin and its Paleozoic and Triassic basement to erosion.

Tertiary Strata. Oligocene to Miocene Tertiary rhyolite volcanic tuffs dominate the capping volcanic units in the area. Some andesitic flows are interbedded within the tuff sequence and a possible Eocene andesite crops out along Baboyahui creek. A late

Miocene or Quaternary basalt crops out in the south central part of the map area but was not separated out during the mapping.

Zataque Igneous Bodies

Igneous bodies cut all but the middle Tertiary volcanic rocks. The main batholithic body in the area is the large mass of Sonora-Sinaloa Granodioritic Batholith mostly located to the south of the Montaña del Oro Property. It intrudes the southern edge of the property in the Zataque area. The batholith may contribute to mineralization at Zataque, but the relationship is not obvious. The sizable andesite feldspar porphyry in the Concepcion-Dura area, although well positioned near the Dura and Concepcion mineralization, lacks alteration and contact effects suggests that it is not likely to be associated with the nearby mineralization.

Zataque Structure

The assumed Bisbee group strata display large amplitude, doubly plunging isoclinal folding with an overall trend of 020°. The folding appears to correspond to the dominant folding episode in the region, near the end of the Cenomanian. The Late Tarahumara andesite units lie on a major unconformity which cuts the strata. The Laramide andesites and Tertiary tuffs show little deformation. Northwest-trending extensional faults mostly cut the Laramide and Tertiary volcanic units.

The veins in the district occur in a variety of orientations. The Chapote and Algarrobes veins mostly trend north, although some 080° veins crop out in the northeast part of the Chapote area. The Zataque, Fronteriza and Don Pablo sets of veins range from 045° to 100°.

MORIS, CHIHUAHUA

The Moris, Chihuahua area occurs near the east end of the east-west offset along the Chihuahua-Sonoran border along the Rio Moris branch at the headwaters of the Rio Mayo. It can be reached by gravel road south from Maycoba, Sonora, located along Highway 16 between Hermosillo and Chihuahua City or west from Cahuizore, Chihuahua (also along Highway 16) through Ocampo, Chihuahua. The purpose of including Moris in the study was to investigate the reported Upper Jurassic strata in the area to fill in the gap in outcrops between Arivechi, Sonora and Batopilas. Radiometric dating of two samples (206 zircons) of paleontologically defined Jurassic strata to confirm these dates was unsuccessful. The sandstones dated appear to be derived entirely from exposed quartzite in the adjacent basement block.

Previous work

The only known publications on the geology of the Moris area are SGM Geology and Mineral maps Tecoripa H12-12 1:250,000 scale map (Garcia Cortez and others, 2000; Fig. 3.36), SGM 1:50,000 scale Geology and Mineral maps Moris H12-D88 (Herrera Galvan and Cabañas Villalba, 2004) and Yepachic H12-78 (Espinosa Arumburu and Canizal Velazquez, 2007). The authors of geologic map H12-78 recognize the presence of Precambrian gneiss at the north end of the area, but the authors of H12-88 indicate that the same unit becomes a Jurassic meta-lutite and meta-limestone at the map boundary. H12-88 also interprets the granite along Santa Maria Creek near the boundary with H12-D78 as Neocomian Lower Cretaceous granite. The Tithonian Jurassic age for the much broader exposed marine shale and volcanic detritus is attributed to foraminifera ages acquired as part of a study by COREMI (Consejo Recursos Minerales, 2003; a predecessor to SGM). In the 50k scale published maps, other than possible undifferentiated limestone in the Jurassic meta-sedimentary rock, most limestone was interpreted as allochthonous Albian limestone.

Geologic Setting

The Moris, Chihuahua region lies within the western portion of the SMOVP along the headwaters of the Rio Mayo. Three K-Ar dates from the SGM database for the Moris geologic quadrangle range from 29 to 26Ma on these volcanic rocks. All older rocks occur in small windows exposed in the SMOVP in the Rio Mayo headwaters.

Cerro el Palmar southeast of Arivechi, Sonora is a popular site for collecting Upper Jurassic ammonites from a black marine shale that is overlain by allochthonous overturned Bisbee Group strata (Almazan-Vazquez, 2000; Monreal, 1997). Cerro el Palmar is located 95 km to the northwest of Moris. Upper Jurassic ammonites are reported from similar outcrops southwest of the Batopilas District (described above), 150 km to the southeast of Moris. The Batopilas Formation hosts ammonites in Upper Jurassic volcanic-rich marine shale that is physically very similar to the outcrops at Moris and are dated as Upper Jurassic (149 Ma) by U-Pb (this study).

Moris, Chihuahua Stratigraphy

The oldest unit observed during this reconnaissance mapping (Fig. 3.37) is a banded gneiss that crops out in Arroyo Santa Maria, the main drainage continuing north from Moris, Chihuahua and cutting across the northern part of the pre-Jurassic exposure between 8 and 13km north of Moris, Chihuahua. The banded gneiss displays no evidence of migmitization (incipient melting) and appears to be derived from a volcanic clastic or possible sediment protolith. The gneiss is cut by an un-metamorphosed granite (Fig. 3.38) along the west side where the Arroyo Santa Maria starts cutting through the gneiss. As a part of this study, the granite was dated and yielded an U-Pb date of 1.44 Ga from 30 zircons (Appendix A and Supplemental Data). The granite contacts do not indicate any relationship to metamorphism of the gneiss, and based on regional data the gneiss is most likely Mazatzal (1.65 Ga) or older. The gneiss and granite are cut by an angular unconformity that strikes 120° and dips 15 to 20° southwest. On this unconformity lies up to 50m of a quartz pebble conglomerate with a quartzite matrix that is capped by approximately 350m of a medium-bedded gray limestone. The quartz pebble conglomerate and limestones lithologically and sequentially correlate most closely with the Lower Paleozoic section of northeastern Sonora and southwestern North America. A second basement block that contains the quartzite and limestone and possibly the gneiss, crops out 1.5km south of the first block. The strata in this block have an azimuth of 090° with a 20° dip to the south.

A deep canyon branching east from the Arroyo Santa Maria cuts through a deep section of volcanic-rich shale and sandstone of marine origin (Figs. 3.39 and 3.41) reported to contain Tithonian foraminifera (Herrera-Galvan and Cabañas-Villalba, 2004). Upper Jurassic ammonites are reported from similar strata (Garcia Cortez and others, 2000) from the Pilar de Moris area 20 km southwest of the mapped area. The basement on the north side of this canyon stands from 700 to 800m above the canyon floor and the basement south of the canyon stands 300 to 400m above the canyon floor. The Jurassic strata continues as much as 300m up on the flanks of both basement outcrops. On the east side of the northern basement block, another outcrop of the marine shale strata continues from the floor of the Rio Moris branch of the Rio Mayo 300m up the side of the basement block where it rest unconformably on gneiss, quartzite, and limestone. Several large bodies of limestone breccia were observed along the east side that are interpreted as landslides off of the basement block into the surrounding Tithonian shale.

Up to 100 m of coarse conglomerate, derived mostly from sedimentary rock strata, rest unconformably on the Tithonian strata (Figs. 3.37 and 3.40). This conglomerate is similar in appearance to a regionally observed unit between the Upper Jurassic strata and lower Upper Cretaceous Tarahumara Formation equivalents. It correlates with the Glance Conglomerate (Garcia Cortez and others, 2000; Terán Martinez and others, 2005). Gently east dipping andesite flows and breccias, found unconformably overlying the conglomerate or underlying shale, continue between the two basement blocks. Although undated, its best regional correlation is with the early Late Cretaceous Tarahumara andesite of the Upper Cretaceous (based on observations at Batopilas and Zataque from this study).

Moris, Chihuahua Structure

The northern gneiss block is cut by an angular unconformity that has a 120° azimuth and dips 15 to 20° southwest (Fig. 3.37). The quartzite and limestone capping the gneiss have the same strike and dip as the unconformity. The southern basement block just north of the Santa Maria Mine has a 090° azimuth with a 20° dip to the south.

The two basement blocks are deeply buried in the Tithonian strata and do not appear to have been tectonically pushed up through the section. The presence of limestone landslide debris within the Tithonian strata (Fig. 3.37) and the Precambrian zircon ages from the Upper Jurassic strata on the flanks of quartzite outcrops suggest the quartzite as a possible source of these zircons, supporting Jurassic deposition around the basement blocks.

East-directed thrusting was observed at the west mouth on the south side of the canyon separating the two basement blocks (Figs. 3.37 and 3.39).

Moris Radiometric ages

Four samples were collected for radiometric ages. One sample each of the gneiss and granite and two samples of the Tithonian strata were collected for provenance ages (all shown on Figs. 3.37). The granite yielded a U-Pb date of 1.44 Ga from 30 zircons (see Fig. 3.38. Appendix A and the Supplemental Data). The gneiss age has not yet been determined.

The two samples from the Tithonian strata did not confirm the Upper Jurassic paleontological age but did confirm that sedimentary debris off the flanks of the basement blocks contributed a major component to the local strata (Fig. 3.39). It is interpreted that the dated zircons were mostly from the quartzite and possibly the underlying gneiss. Sample JLMS-1 is dominated by the Mesoarchean and Neoarchean zircons (ranging from 3,084 to 2,527 Ma, with a peak age of 2,751 Ma from 65 of 96 zircons) and Paleoproterozoic zircons (ranging from 2,480 to 1,705 Ma with a peak age of 1,838 Ma from 30 of 96 zircons, see Appendix A). Sample JLMS-2 is more complex with similar Mesoarchean and Neoarchean zircons (ranging from 3,052 to 2,545 Ma with a peak age of 2,725 Ma, from 61 of 100 zircons) and Paleoproterozoic zircons from the Mazatzal and Yavapai (ranging from 2,475 to 1,690 Ma with a peak age of 1,838 Ma from 36 of 100 zircons). In addition to these similarities JLMS-2 also contains three Late Mezoproterozoic zircons from 1,106 to 1059 Ma (3 of 100 zircons) reflecting the Grenville Province age (see Appendix A and Supplemental Files).

One possible interpretation of the differences in zircon relative probability plots of these two samples is that JLMS-1 reflects detritus from the gneiss with more limited zircon populations and JLMS-2 reflects detritus from the quartzite with a broader range of zircon ages.

BATOPILAS TRANSECT

Mapping of the various mineral prospects of Batopilas and Lluvia del Oro, Chihuahua and Zataque (Montaña del Oro) along with regional reconnaissance mapping allows for the construction of an interpretive cross-section through the western coastal area of Mexico near the tri-state area of Sonora, Chihuahua and Sinaloa (Fig. 3.42). This cross-section uses no vertical exaggeration, producing a very compressed appearing view over its 290km length (Fig. 3.43). For this reason the cross-section is also shown in two 170km long overlapping blowups to better show the interpreted structure (Fig. 3.44 and 3.45). Listric faults were chosen to accommodate the up to 150 km of shortening required to produce the Mezcalera Overthrust. Not a lot is known about the deeper structural behavior, but what is known includes the low angle west-directed nature of thrusting in the Upper Jurassic strata at Batopilas and a limited view of the Mezcalera Overthrust structure based mostly on one deep Pemex exploration hole Parral-1 (Grajales-Nishimura, 1992). In addition to the fact that the overthrust overrides platform strata equivalent to that on the Coahuila Platform, we can infer that the Paleozoic crust exposed along the west margin of the Mezcalera Overthrust is the same crust as that which underlies the platforms to the east. Evidence for this interpretation comes from the ages of the exposed crust that have long been recognized as similar in age and greenschist degree of metamorphism to other exposures of Ouachita Paleozoic crust to the east. The newest evidence that the so called Parral Terrane is not an accreted terrane is the fact that Lower to Middle Jurassic Nazas volcanic and clastic rocks rest on the schist in the SA14-18 drill hole at Salamandra (Sierra Piojo) 37 km east of Durango City. This indicates that this basement block was part of the platform on what the Nazas was deposited prior to the beginning of the Jurassic and not part of a Middle Cretaceous suture zone (Dickinson and Lawton, 2001).

From the presence of a minimum of 1,000 m of Jurassic deep marine strata and turbidites with bedded and vent facies submarine andesitic volcanic rocks in the Batopilas area and similar strata at Moris, Chihuahua with a smaller volcanic component, it can be interpreted that a major Jurassic basin is transected by this cross-section.

STRUCTURAL ELEMENTS ASSOCIATED WITH MEZCALERA BASIN

Following the presentation of evidence for the continuation of a Jurassic marginal basin along the western coast of Jurassic Mexico from the previously documented Papago and Cucurpe basins down through Moris and Batopilas, Chihuahua, related structural elements that assist the building of this model will be presented. They include the Mezcalera overthrust, the Durango inverted basement block and the Sonora-Sinaloa transpressional fault.

Mezcalera Overthrust

The Upper Jurassic through Lower Cretaceous Mezcalera Formation is a widely mapped unit in west central Mexico and is included in most published Mexican maps covering its exposure (Carrizales and Prian, 2000; Prian and others, 2000; De Santiago-Cespedes and others, 2000; Munguia and others, 2000). These authors present the Mezcalera Overthrust as a belt of rock resting on Paleozoic basement named the Tesoro Formation. It is being covered here because all evidence indicates that it was derived from severe shortening of the marginal basin to the west of the Mezcalera Overthrust Belt.

Highly variable rise and slope strata consisting of laminated to thin bedded mud deposits and minimal graded bedding interpreted as overbank deposits of turbidite channels and turbidite deposits from the marginal basin with some distal shelf carbonates (for example Cazaderos, Zacatecas) make up the majority of the Mezcalera Group strata.

The Parral, Chihuahua mineral district is contained within these upper plate rocks along with Oligocene volcanic rocks

In the mineral industry the overthrust had long been called the Parral-Proaño overthrust, named for the Parral Formation in the Parral District and the Proaño Formation of the Fresnillo District both in upper plate rocks. The petroleum industry working separately named it the Mezcalera overthrust for an obscure outcrop northeast of Parral which led to its adoption by the academic community and it has become the most widely accepted term. Pemex exploration drill hole Parral-1, 72 km southeast of Parral, confirms that the Mezcalera Lower Cretaceous and Upper Jurassic deep shelf turbidites and rise and slope strata are thrust over the Lower Cretaceous platform carbonates that are resting on the Middle Jurassic Nazas Formation (Grajales-Nishimura, 1992).

The Mezcalera overthrust (Fig. 3.47) was thrust east out of the marginal basin in the Late Cenomanian as documented by the age of the rock units involved in the thrust. As noted above, a mineral exploration drill hole 37km east northeast of downtown Durango cut 140 m of Upper Cenomanian Indidura Formation that contains debris flows of probable Albian limestone. This drill hole also cut 210 m of welded tuff and poorly sorted sandstones interpreted to be Nazas Formation, underlain by 80 m of probable Permian schist. The presence of the Nazas resting on the Paleozoic schist indicates that the schist was in place before any Lower or later Cretaceous suture event.

Durango Inverted Basement Block

Exposures of schist are known to occur from Valle de Olivos northwest of Parral, Chihuahua to Santa Maria del Oro, Indé, and San Lucas del Ocampo, Durango. Santa Maria del Oro outcrops have been dated as Mississippian (326 Ma by K-Ar, referenced in

Poole and others, 2005) and San Lucas del Ocampo as Permo-Triassic by K-Ar and Ar-Ar (Iriondo and Premo, 2010).

Indé and Santa Maria del Oro, Durango. The Indé and Santa Maria del Oro gold districts Durango are situated in an area of complex geology along the boundary between the Mezcalera klippe and the inverted Paleozoic basement. Segments of Nazas andesite overlain by La Joya conglomerate overlain by Zuloaga limestone crop out along a thrust boundary of Paleozoic schist. The Mezcalera Formation sometimes displays slaty cleavage over a large area. The Tesoro Formation, usually a schistose rock, is separated from the Mezcalera by a fault boundary. Dating of these rocks has resulted in a wide range of ages ranging from Ordovician to Mississippian and Pennsylvanian. to Lower Jurassic. It is not clear if everyone is dating the same rock. The slates that Aranda and others (1982) dated as Lower Jurassic from pollen match what has been mapped in this study as Mezcalera. The schist and mélange (chaotic mixes of Paleozoic and volcanic debris of mud and sand to blocks of a scale of 100's of meters) have numerous Paleozoic metamorphic ages in the belt from Santa Maria del Oro south to San Lucas del Ocampo, dated at 251 Ma (Poole and others, 2005; Iriondo and others, 2003).

San Lucas del Ocampo, Durango. San Lucas del Ocampo, Durango is located 70 km north of Durango City (Fig. 3.46) along the Pan American Highway to Parral, Chihuahua. Several kilometers north of San Lucas several outcrops of graphitic mica schist cut by abundant white metamorphic quartz veins and tectonic breccias are indicated on the Durango 1:250,000 scale G13-11 geologic quadrangle (Munguia and others, 1998). These schist outcrops have been dated several times, the most recent being an Ar-Ar age of 251 Ma (Iriondo and others, 2003).

The structural fabric of the schist is east northeast dipping 20° south. This fabric is consistent with the metamorphic fabric observed in many known and suspected occurrences of Paleozoic Ouachita age basement in the proposed area of Paleozoic basement in north central Mexico.

Volcanic rocks exposed along the northeast flank of the exposure of schist are interpreted as Nazas by lithologic comparison but have not been dated.

Salamandra, Durango. Salamandra, Durango Prospect is located 37 km east northeast of the city of Durango (Fig. 3.46). The oldest outcrops consist of Cenomanian to Turonian Indidura and Agua Nueva Formations that in turn are cut and covered by interpreted Eocene Dacite to Rhyodacite dikes and flows. The Indidura contains distinctive 3mm mudstone laminations characteristic of the unit. This complete package is covered by Oligocene welded tuffs exposed 2km to the east in a 15km long ridge Cerro Pilar. The Eocene age is estimated from the oldest volcanic rocks previously dated in the region by K/Ar at 51.6 Ma and the K/Ar Oligocene ages obtained from the overlying welded tuffs (Swanson and others, 1978).

At Salamandra, limestone debris flows within the Indidura contain cobble size coarse grained limestone fragments with fragments of broken fossils. The most likely source of these limestone cobbles are believed to be Albian Aurora reefs that were eroded from the inverting basement blocks to the west of the area during deposition of the Indidura in the Turonian.

In drill hole SA14-18 on the western side of the prospect, the upper 100m of core consisted of Indidura that contained limestone debris flows mentioned above. The next 150 m consisted of a rhyodacite welded tuff lithologically similar to an outcrop of Nazas welded tuff near Guzman west of Torreon dated at 165 Ma (Lawton and Molina-Garza, 2014) and the Nazas welded tuff of the inverted basement at Sierra Ramirez, Durango (171 Ma, this study sample JLSR-01, see Appendix A). Underneath the volcanic unit in SA14-18 are 200 m of graphitic mica schist with white metamorphic quartz veins, essentially identical to the Late Permian (251 Ma) schist at San Lucas del Ocampo, Durango 70 km to the north of Salamandra. Samples have been collected for dating of the presumed Nazas and Paleozoic schist, but the analysis have not yet been performed.

The property is interpreted to rest on a major reverse fault separating an inverted Paleozoic basement block on the east edge of the Mezcalera marginal basin from the stable Ouachita basement to the east through a series of step faults stepping down to the east.

Sonora-Sinaloa Transpressional Fault

The Mojave-Sonora Megashear (MSM) hypothesis was proposed by Silver and Anderson (1974) to explain an isotopic discontinuity between Precambrian basement domains in northwestern Sonora (Fig. 3.78). Jones and others. (1995) invoked a left-lateral offset of 700 to 1000 kilometers on the MSM to link the Mid-Jurassic silicic volcanic field of northern Sonora to similar volcanic rocks of the Nazas Formation in central Mexico. Terrane models (Campa and Coney, 1983; Sedlock and others, 1993) proposed that the MSM constitutes an important terrane boundary between the Caborca, Guerrero, Chihuahua and Sierra Madre Oriental Terranes, bringing these tectonostratigraphic terranes into their present, pre-Sierra Madre Volcanic Belt positions sometime prior to the Cretaceous. Extensive cover of the Late Cretaceous-Tertiary Sierra Madre Occidental Tertiary volcanic field renders it difficult to prove or disprove this offset. Although the MSM translation is hypothesized to have brought the Caborca Terrane to its present position in the Mid- to Late Jurassic (Campa and Coney, 1983; Anderson and Silver, 2005), only structurally complex zones as at Caborca-Santa Ana (Jacques-Ayala, 1995) and Cerro de Oro (Gonzales-Leon and Jacques-Ayala, 1995) along the projected fault trace have been interpreted to have Bisbee Group strata on the Caborca terrane basement (Fig. 3.48). Complex thrusting is typical along the fault, and the known presence of extended basement blocks in the floor of a proposed Mid-Mesozoic marginal basin (Lyons, 2008) opens the possibility of structural or depositional placement of Bisbee Group on inverted blocks from an extended marginal basin floor. The metamorphic basement capped by a basal quartzite and Permian rocks at Cerro de Oro (Radelli and others, 1996) is more consistent with the cratonic crust to the east than the thick Proterozoic carbonates reported on the Caborca Terrane (Anderson and Silver, 2005). Otherwise Bisbee-age rocks found within the Caborca block lack the distinctive stratigraphic succession of the type Bisbee Group (Ransom, 1904) that characterizes the Bisbee throughout northeastern Sonora (Rosales-Dominguez and others, 1995, Jacques-Ayala, 1995). This raises further doubt as to whether the Caborca terrane had reached its present position by the Early Cretaceous.

Dickenson and Lawton (2001) proposed a two stage history along a structure similar to the MSM, the California-Coahuila Transform (CCT, Fig.3.46). They proposed the CCT based on data from California (Dickenson, 2000) with the Caborca Terrane being emplaced along the California-Coahuila transform in the Early Permian. Motion further East along the CCT is proposed between the Middle Triassic and Middle Jurassic.

Regional and detailed mapping in northern Mexico by the author over the past 25 years provided a geologic context of basin geometries and timing of tectonic events related to these basins. This knowledge improved interpretation of igneous and detrital zircons for which U-Pb dating has encouraged major reinterpretations of the geology of the region (Lyons, 2008).

Regional setting. Precambrian basement with Paleozoic supercrustal cover crops out in northeastern Sonora (Mazatzal Province) and northwestern Sonora (Mojave and Yavapi Provinces of the Caborca Terrane, Iriondo and Premo, 2010). A belt of limited basement exposures first recognized in southwest Arizona, the Papago Terrane (Haxel and others, 1980) is now documented from north central Sonora to at least as far south as Durango and has been interpreted as a Mesozoic marginal extensional basin (Lyons, 2008). A thick succession of Middle Jurassic dacitic to rhyolitic volcanic tuffs and flows cover the Paleozoic and older basement across northern Sonora but does not correlate with Mid-Jurassic andesite-dominated strata found south of the proposed MSM. A 700 to 1000 km of offset on the MSM was proposed based on the concept that the northern Sonora Jurassic silicic volcanic rocks were offset to central Mexico where they are represented by the Mid-Jurassic Nazas volcanic units (Jones and others, 1995).

The Lower Cretaceous Bisbee Group of southeast Arizona and northern Sonora, as defined by Ransom (1904) from exposures in the Mule Mountains near Bisbee, Arizona, consists, in ascending order, of the Glance Conglomerate overlain by the Morita, Mural and Cintura Formations (Fig. 3.49). The basal Glance Conglomerate displays a highly variable lithic content and thickness. It is an apparently locally derived conglomerate with sparse limestone and tuff beds. The Mortita Formation consists of fluvial sandstone and shale, in part reworked by marine transgression. The Mural Formation consists of reefal carbonates and lagoonal calcareous shales with some mixing with reworked fluvial sands. The Cintura Formation consists of regressive fluvial and deltaic strata (Rosales-Dominguez and others, 1995; Jacques-Ayala, 1995).

Lawton and others. (2003) and Anderson and Nourse (2005) attributed the formation of Late Jurassic basins found in northern Sonora such as the Cucurpe and San Antonio basins to pull apart basins formed at bends in the Late Jurassic MSM. Lyons (2008) proposed that the scattered distribution of Upper Jurassic marine exposures from north central Sonora to southwestern Chihuahua (Cucurpe, Taupe, Aconchi, Chinos-Conchas, Moris, and Batopilas; Fig. 3.48) is more indicative of a continuous cratonic marginal basin formed by late Triassic to Late Jurassic rifting of the western Mexican cratonic margin. This extensional environment is best explained by slab rollback of the adjacent subducting oceanic crust, indicated by the increasing evidence of westward migration of the arc from the Permian to the Early Cretaceous. This basin is referred to as the Mezcalera Marginal Basin. Precambrian basement capped with Paleozoic quartzite and carbonates under Jurassic marine strata observed at Aconchi and Moris and beneath Bisbee Group strata at Cerro de Oro are interpreted as extended cratonic crust flooring the marginal basin (Lyons, 2008).

Northern Sonora Bisbee Group outcrops. Measured sections in the Bisbee Group strata at Santa Ana (Jacques-Ayala, 1995) in north central Sonora and at Rancho Culantrillo (Rosales-Dominguez and others, 1995) in northeast Sonora (Fig. 3.48) demonstrate the two fossiliferous limestone units separated by calcareous lagoonal shale typical of the Mural Formation. In an overturned section at Cerro las Conchas (Fig. 3.48) in east central Sonora, the Mural consists of two limestones separated by calcareous shale (Monreal-Saavedra, 1997). This stratigraphy is typical of all Mural exposures documented during this study. Reported variations (e.g. Lawton and Olmstead, 1995) appear to relate to increased clastic sediment input near the basin margins.

One previously unreported occurrence of Bisbee Group strata in northern Sonora was found during this study. In Sierra Manzanal (Mnz, Fig. 3.48), isoclinally folded Mural Formation and adjacent Cintura Formation underlie a major unconformity at the base of tilted Middle Upper Cretaceous Cabullona Group.

Sonora-Chihuahua-Sinaloa Border And Northern Sinaloa region. Numerous occurrences of possible Bisbee Group strata showing the distinctive Morita-Mural-Cintura lithologic succession have been recognized in the tri-state border region of Sonora, Chihuahua and Sinaloa. Scattered occurrences are found for more than 70 km to the southwest and 400 km to the south-southeast of the tri-state junction into Sinaloa, where they are greatly affected by the batholith. They have not been observed to the north for more than 200 km until the Conchas area (Fig. 3.48). The best preserved examples are at Lluvia del Oro (LdO), Reforma (Rfr), Concepcion (Cnc) and Zataque (Ztq) Fig. 3.48) where Cintura- and Morita-like intervals of marine sandstone and shale and fluvial-deltaic clastic strata are separated by rudist-bearing reefal limestones with intervening lagoonal calcareous shale. Exposures with less definitive lithologies have been noted at El Gallo-Magistral (GMg, Fig. 3.48), where a limestone skarn is overlain and underlain by sandstones, all now standing vertically, and unconformably overlain by weakly tilted andesitic units. Additional occurrences of metasomatized limestone in the region west of Zataque and south to Santa Cruz Alaya (SCA, Fig. 3.46) possibly correlate with Bisbee Group strata but are too altered by the Sonora-Sinaloa batholith for definitive correlation.

An important outcrop worthy of more study is the occurrence of Rhyolite tuffs and volcanoclastics observed at Mapiri-Magistral (MMg, Fig. 3.48) that show strong similarities with deuteric alteration and hundreds of meters of thickness observed north of the Caborca Block in northwesternmost Sonora.

At Lluvia del Oro (Fig. 3.48), a succession of sandstone and shale, limestone, calcareous shale, a younger limestone and overlying sandstone is exposed in a syncline cut by an unconformity with hundreds of meters of relief. Conglomerate and sandstone units partially fill paleocanyons on the high relief unconformity, and regionally tilted andesite flows and breccias complete the burial of the unconformity. The solution cavities of the heavily karsted limestone exposed beneath this unconformity are partially filled with the overlying sandstones, conglomerates, and andesites. Zataque exhibits the same stratigraphic sequence as Lluvia del Oro, but with tighter isoclinal folding. This succession is also truncated by a major unconformity overlain by sandstone and conglomerate, and capped by gently dipping andesite.

East of Lluvia del Oro at Batopilas (Fig. 3.48) tilted Upper Cretaceous volcanic rocks overlie deep marine Jurassic sediments of the marginal basin (Lyons, 2008).

Structure. Late Cretaceous deformation of the Bisbee Group northeast of Cananea consists mostly of high angle reverse faults cutting Mazatzal age Pinal schist (~1650 Ma). Southwest of Cananea, outcrops of basement are rare as recognized in southwestern Arizona (Haxel and others, 1980). The folds observed across the Jurassic marginal basin (Lyons, 2008) are generally broader in the central basin and isoclinally folded or thrusted along the margins, indicative of basin inversion. Complex structural relations observed by Mauel (2007) at Cucurpe (Figs. 3.46, 3.47, 3.48) with probable underlying extended crust require ≥50% shortening (Lyons, 2008). The boundary between the Caborca terrane and the marginal basin to the east is a complex thrust zone with possible inverted blocks of extended crust. Gonzales-Leon and Jacques-Ayala (1988) documented thrust features along the boundary at Cerro de Oro (Fig. 3.48), while Pubellier and others, (1995) documented similar thrusting relationships along it at Chiltepin and Conches (Fig. 3.48). The Bisbee strata at Conches are interpreted as overturned (Monreal, 1997).

The Bisbee equivalent strata at Zataque and Lluvia del Oro (Fig. 3.48) exhibit isoclinal folding with NNE axes and show complex fold and thrust relationships with the adjacent outcrops of Jurassic pelagic and turbiditic strata. Upper Cretaceous cover at Magistral prevents full unraveling of the local mid-Cretaceous tectonism, but the contact between the lower Cretaceous platform strata and the Cretaceous marine sedimentary and volcanic rocks to the east appears to be a west-directed thrust.

Detrital Zircon Ages. At Zataque (Fig. 3.48) detrital zircon U-Pb dates are consistent with the stratigraphic correlation described above. Pb-U dates were determined on zircons from a tuffaceous bed (JL-MO-1) several tens of meters stratigraphically below the lower limestone and others from a coarse conglomerate (JL-MO-2) approximately 1 km up section from the major unconformity separating the two units. Zircon U-Pb dating indicates that the tuff is 132-138 Ma (sample JLMO-01, Appendix A). Zircons from the unconformably overlying coarse clastic strata contain principally 75 to 100 Ma zircons (sample JLMO-02, Appendix A) plus significant concentrations of late Jurassic and Permo-Triassic zircons.

Discussion. The discontinuous distribution of outcrops of Upper Jurassic volcanic-rich marine pelagic and turbiditic strata in northern to central Sonora and constraints imposed by the postulated MSM have led to placing these marine units in separate transtensional pull-apart basins (see Anderson and Nourse, 2005 for a more complete discussion). None of these models address the existence of Upper Jurassic marine strata south of the MSM. Documentation of numerous outcrops of Jurassic deep marine units suggests that it may be more appropriate to define the region as a continuous marginal basin (Lyons, 2008). These marine strata are locally found draped over fault blocks of apparent extended crust (e.g. Moris), that match the adjacent craton to the east. The geological and chemical definition of the Guerrero marginal basin (Lyons, 2008) challenges the existence of the MSM because there is no offset apparent on this Jurassic basin. Bisbee Group strata overlie the Jurassic basin in northern Sonora between Caborca, and the North American continental crust and was documented to continue south past Chinos-Conchas (ChC, Fig. 3.48). Bisbee Group strata were not observed overlying the Upper Jurassic marine strata at Moris and Batopilas (Fig. 3.46, 3.48) but are interpreted to lie west of the Sonoran-Sinaloa Transpressional fault proposed by this study. A sedimentary succession mapped in the Sonora-Sinaloa-Chihuahua tri-state area at Lluvia del Oro and Zataque (Fig. 3.49) strongly correlates with Bisbee Group strata from northern Sonora. These strata continue south-southeast into Sinaloa as least as far as the Magistral mining district (Fig. 3.48) and are separated from the Mexican Craton by Jurassic and Cretaceous deep marine and slope units.

The thick rhyolitic tuffs of northwestern Sonora appear absent southwest of the SSF. Now similar units have been mapped 700 km to the south on the southwest side of the SSF in the Mapiri area (Fig. 3.46). Similar occurrences apparently are absent in the intervening region.

The Aptian-Albian shelf environment in southern Chihuahua lacked coarse fluvial sources to feed the massive sandy Morita and Cintura equivalents seen in Sinaloa as are known to have fed the Bisbee basin of northern Sonora.

The apparent offset of Bisbee correlative strata and Mid-Jurassic rhyolite tuffs 600 to 700 km south southeast with associated isoclinal folding indicates significant transpressional motion. The approximate width across the Bisbee Basin on both sides of this newly proposed fault measures on the order of 300 to 400 km. In addition to a strong lithologic correlation between the two areas, detrital zircon ages indicate the folded limestone beds of the Sonora-Sinaloa-Chihuahua border region most likely correlates with the Mural Formation of the Bisbee basin.

Conclusion. Despite being variably altered by Upper Cretaceous intrusive activity, outcrops of apparent Bisbee Group strata have been documented to continue as a discontinuous belt from Lluvia de Oro-Reforma, Chihuahua (Fig. 3.48) SSE through the Mapiri- and Gallo-Magistral District, Sinaloa (Fig. 3.48). Recrystallized carbonate strata in the Cosala and Santa Cruz Alaya are tentatively interpreted as the equivalent platform carbonate sequence found at Lampasos (Fig. 3.48). The distinctive Bisbee Group strata appear offset from the known Bisbee Basin of northern Sonora-southern Arizona by about 600 km of left-lateral motion along a transpressional fault herein called the Sonora-Sinaloa Fault (SSF, Fig. 3.48). The left-lateral strike-slip component of the SSF is indicated the by numerous apparent offsets of geologic features discussed above it is often obscured by at least 100 km of eastward directed thrusting from the shortening component. The 600 km separation of probable Jurassic rhyolitic volcanic rocks exposed beneath the Cretaceous strata at Mapiri in the Magistral District (Fig. 3.48) from those known in northern Sonora is consistent with the proposed displacement of the SSF.

Isoclinal folding of the Lower Cretaceous Bisbee Group unconformably beneath tilted Upper Cretaceous strata (Tarahumara and Cabuona) on the northwest side of the SSF in northern Sonora and the southwest side of the SSF in Sinaloa further supports Cenomanian timing for the SSF. The most intense folding of the Bisbee strata occurs where these units overlie Jurassic marine strata, reflecting the greater structural shortening (basin inversion) of the marginal basin as opposed to un-extended adjacent crust.

DISCUSSION: PASSIVE JURASSIC FOREARC TO LOWER CRETACEOUS BACK-ARC BASIN

Widely accepted components of tectonic models along the western boundary of the Mexican Craton consist of (1) the Mojave-Sonora Megashear (Silver and Anderson, 1974; Anderson and Silver, 2005a), a transform fault that cuts diagonally across northwestern Mexico with as much as 1000 km of left lateral offset; (2) the Guerrero Terrane (Campa and Coney, 1983) a succession of an oceanic arc and ocean floors accreted to southwestern Mexico; (3) the Caborca Terrane (Campa and Coney, 1983) a Precambrian block proposed to have migrated to its present location from California between the Late Jurassic along the Mojave-Sonora Megashear (Anderson and Silver, 2005a); and (4) a Late Pennsylvanian to a middle Early Triassic offset along the California-Coahuila Transform (Dickinson and Lawton, 2001). An additional proposed tectonic component is (5) the Paleozoic outcrops along the west edge of the Mezcalera Overthrust comprise another accreted terrane or accreted debris in a suture zone the Parral Terrane, made up of Tesoro Formation (Dickinson and Lawton, 2001). They continue this suture zone northwest across Sonora to include the Cortez zone. One model (6) that diverges from most suggests a continuity of the Paleozoic strata between the Ouachita-Marathon Orogenic belt on the south central side of the North American craton with similar aged strata in Sonora (Pool and others, 2005).

Important tectonic elements described or alluded to in the literature have not been incorporated into the major models. They include the Papago Terrane (Haxel and others, 1980, 1984), the Jurassic Cucurpe basin (Lawton and others, 2003; Mauel and others, 2011), Upper Jurassic marine strata at Sahuaripa (Pubellier and others, 1995), Arivechi (Garcia Cortez and others, 2000), Upper Jurassic marine strata at Moris, Chihuahua protruded by two blocks of Precambrian basement through Paleozoic strata (Herrera-Glavan and Cabañas-Villalba, 2004), Middle to Upper Jurassic marine strata at Topia, Durango (Esquer Mundo and others, 2001), Bacis, Durango (Servicios Cartographicos del Noroeste, 2001) and Jurassic marine strata at Copala and Rosario, Sinaloa (Garcia-Padilla and others, 2000; this study). Campa and Coney (1983) gave the Papago an interrogative that is the only reference to the Papago Terrane in widely referred to tectonic models (Sedlock and others, 1993; Dickinson and Lawton, 2001).

Basin Terminology

Basin terminology is not straight forward with regards to this Jurassic basin. Continental margin basin is a self-explanatory generic term that normally applies to passive margins. It consists of shelf, slope and rise deposits (Emery, 1977). Forearc and back arc basins describe the position of the basin in reference to the volcanic arc; forearc- between the arc and the subducting oceanic arc and back arc- away from the arc in relation to the subducting plate. Seely and Dickinson (1977) discuss the situation where the arc moves across the basin changing it from forearc to intra-arc to back arc but offer no inclusive term for a basin that has evolved through various arc positions.

The Jurassic Basin appears situated along the west margin of the Mexican Precambrian and Paleozoic craton like a marginal basin. It differs from the classic marginal basin in that it is situated in an arc environment. Application of back arc and forearc terms to the basin is complicated by the fact that the arc migration crosses over the basin in the late Jurassic. The alternative seems to be calling it a marginal or continental margin basin as it has many sedimentary features of a marginal basin.

The ocean-ward arc migration may best be explained by the slowing of the rate of subduction that results in a steeper sinking angle of the oceanic plate thus bringing the zone of melting closer to the beginning of the subducting plate. In addition, the slowed subduction rate results in less depression of the isotherms as the subducting plate has more time to heat, again bringing the plate melting point closer to the surface and closer to the subduction zone.

This rollback of the subducting plate to a steeper angle and assisted by rising asthenosphere produced an extension environment inboard from the arc. This back arc extension produced an environment that appears more likely to have produced the intracratonic basins subparallel to the coast than a left lateral pull-apart mechanism related to the opening of the Gulf of Mexico.

Jurassic Marginal Basin Fill.

Upper Jurassic marine strata can be found from southwest of Nogales, Sonora through the Cucurpe region to Sahuaripa and Arivechi, Sonora, Moris, Chihuahua and the new discovery of Upper Jurassic strata at Batopilas, Chihuahua (Fig. 3.12.1). These Jurassic strata continue to Topia and Bacis, Durango, and Copala and Rosario, Sinaloa. Isolated occurrences of similar strata have been observed south to and beyond the Trans Mexican Volcanic Belt well within the Guerrero Terrane. The Upper and possibly Middle Jurassic strata contain deep marine shale and mud, widely variable turbidite facies from thin laminar outflow to thick graded bedding and debris flows. Commonly turbidites are fossiliferous with ammonites, belemnites and micro-fossils with gravity flow fossil hashes from Zuloaga carbonate platforms rich in nerinia, corals and clams. These fossil rich basal debris flows to turbidites show strong westerly alignment of elongate fossils such as belemnites and nerinia. They include variable andesitic to dacitic volcanic content with the most documented at Batopilas including submarine dacitic to andesitic flow domes with breccia carapaces and ash, lapilli and bomb size debris in the surrounding strata. The volcanic debris is strongly intermixed with the fossilierous strata near the domes.

Jurassic deep neritic shelf facies is found in the Mezcalera Overthrust in and near Parral, Chihuahua. Further south in the San Fermin, Durango area, the Jurassic rise facies is more common.

The basin fill ages at Cucurpe (Villaseñor and others, 2005), Arivechi, Moris (Herrera and Cabañas, 2004) and Topia (Esquer Mundo and others, 2001) are obtained from the fossil record. At Cucurpe (Mauel and others, 2011) and Batopilas (this study) the age is based on zircons from included volcanic debris.

Lower Cretaceous Marginal Basin Fill.

Classic Bisbee Group strata cover both the Upper Jurassic marginal basin strata in north central Sonora and the supracrustal Paleozoic strata on the craton in northeastern Sonora into southern Arizona but do not continue westward onto the Caborca Terrane. Distinctive structural styles deform the Bisbee Group depending on the underlying basement. On the craton the Bisbee Group rests on every unit from Precambrian to Jurassic volcanic rocks, and high angle reverse faults characterize most Bisbee Group deformation (Gonzales and Lawton, 1995). The most complex deformation on the craton occurs as gravity glide blocks along these uplifts. The marginal basin boundary with the craton is defined by a belt of significant folding from tectonic shortening within the Bisbee Group strata over the marginal basin strata.

Capping the Bisbee Group strata are an angular unconformity overlain by a siliciclastic sequence with great variability in thickness. Karst developed at the unconformity where it cuts limestone. No folding was observed above the unconformity in the basin, but they are deformed by high angle reverse faults on the craton (Gonzales and Lawton, 1995). The clastic strata overlying the angular unconformity are capped by subaerial andesitic strata throughout northern Sonora and continuing to most areas mapped in the canyons of the Sierra Madre Occidental.

The Jurassic marine rise deposits continue into the Moris and Batopilas areas of southwestern most Chihuahua. South of Arivechi, Sonora, Lower Cretaceous shelf strata have only been observed at Gochico, Sonora and at Chirimoyo, Durango. These thin bedded calcareous mudstone and shale strata are interpreted as distal turbidity flows possibly from main turbidity flow channels based on their weak graded bedding. They appear lithologically similar to the strata of the same age found in areas of the Mezcalera Overthrust at Parral, Durango and east of Santa Maria del Oro, Durango. West of

Gochico, a sequence of strata identical to the Bisbee Group of northern Sonora is in thrust contact with the same age deeper water shelf strata. These Bisbee Group correlatives include strata equivalent to the Morita, Mural and Cintura Formations. South of Gochico the Bisbee Group correlated strata are thrust over the local Mezcalera Marginal Basin strata between 50 to 60 km to the east in the Lluvia del Oro, Chihuahua area.

Marginal Basin Floor.

At Rio Fuerte and Jose de Gracia, Sinaloa, detrital zircons and microfossils document the Paleozoic age (Carrillo-Martinez, 1971; Mullan, 1978; Vega-Granillo and others, 2008, 2011). At Moris the basement is estimated to be at least Mazatzal (1.65 Ga) based on it being cut by a 1.44 Ga granite (dated by U-Pb zircon, this study) and the Jurassic sandstones on the flanks of these basement highs reflect the Precambrian source of the basal quartzite resting on the basement (this study). The gneiss has not been dated, but being cut by 1.44 Ga granite indicates a Mazatzal or older age for the gneiss. Paleozoic interpretations often are based on the degree of metamorphism attributed to the Ouachita orogeny, although that can be locally complicated by Late Cretaceous stocks within the metamorphosed area.

The interpretation presented here is that the various Paleozoic and Precambrian basement blocks observed in the proposed Upper Jurassic marginal basin are elevated areas of the extended crustal floor of a rifted margin that hosts an Upper Jurassic and Lower Cretaceous marginal basin rather than exotic crustal fragments accreted to the craton or a continuous crust underlying the basin. These possible extended crustal blocks include Precambrian basement and Paleozoic strata at Moris, Chihuahua that is now documented to have protruded into the Upper Jurassic marginal basin strata during its deposition (see Moris above and Appendix). Cambro-Ordovician strata at Cerro

Mogallon (Almazan-Vazquez, 1989) and Ordovician strata at Rio Fuerte, Sinaloa (Mullen, 1978; Vega-Granillo and others, 2011), Morelos (Servicios Geologicos Mineros, 2010; and a field review for this study), and Jose de Gracia, Chihuahua (Carrillo-Martinez, 1971; Pool and others, 2005) are documented Paleozoic outcrops. The Morelos outcrop is possibly a batholithic roof pendant which would explain the intense metamorphism if it is Jurassic strata that is not normally metamorphosed to this degree. The Morales gneiss and schist appears more indicative of typical Paleozoic crust, based on the author's extensive observations.

Marginal Basin-Craton Boundary.

The many east northeast-trending bands of Proterozoic through Paleozoic crust of the North American Craton appear to terminate at a relatively straight northwest-trending boundary that passes on the west sides of both the Cananea and the Nacozari Copper Districts of northern Sonora (Cananea Trend). This boundary also corresponds to the boundary between the Mazatzal age crust (1.6 to 1.7 Ga) and the Papago Terrane of Haxel (1980), an area lacking basement older than Jurassic in southwestern Arizona.

The limited occurrence of Pre-Jurassic basement characterizes a belt that projects from Haxel's Papago Terrane (Haxel and others, 1984) in northern Sonora to the Cucurpe area into southwestern Chihuahua and Durango. Southeast of Batopilas there is a gap in the observed data on outcrops of the Upper Jurassic marine strata until Topia, Durango. South southeast of Topia outcrops again become more common to 23° latitude. Scattered outcrops have been observed in southern Mexico south to the state of Guerrero. The Allochthonous basement is known to project over the folded Upper Jurassic and Lower Cretaceous strata in south central Arizona near the Mexican border (Haxel and others, 1984), in the Teguachi (Cucurpe) area (Mauel and others, 2011) and the Sahuaripa and

Arivechi areas (Pubellier and others, 1995). There appears to be an overthrust of Bisbee Group correlative strata over marginal basin strata in the Reforma, Chihuahua area as indicated in the regional cross-section and reconnaissance mapping, but the mapping needs to be expanded to verify this.

Marginal Basin Eastern Edge

The eastern margin of the marginal basin appears to be a rifted boundary between the North American craton and the Upper Jurassic strata. After following the boundary along the porphyry copper related Cananea Trend from southwestern Arizona, it disappears under the Sierra Madre Volcanic Province and reappears as an inverted Paleozoic rifted basement block in central Mexico with the western margin still buried under SMOVP. Limited outcrops west of this boundary define an Upper Jurassic basin that is aligned against this cratonic margin. This basin is characterized by Upper Jurassic deep water marine shale with a major volcanic component, turbidites of which some have a significant debris component from the Upper Jurassic carbonate shelf, and banded deep platform strata of the early Cretaceous. Small exposures of pre Upper Jurassic basement crop out in the Upper Jurassic strata. The documented exposures include Nopalera north of Moris, Chihuahua, the Rio Fuerte Formation north of El Fuerte, Sinaloa, San Jose de Gracias, Sinaloa, the belt of Paleozoic crust in the Choix, Sinaloa area (Vega-Granillo and others, 2011), and a possible Paleozoic roof pendant at Morelos, Chihuahua. Nopalera, remapped for this study, consists of two exposures of pre-Jurassic rocks separated by Jurassic marine strata exposed in a canyon floor. The northern exposure has 700m of relief on a gneissic basement cut by 1.44 Ga granite capped with a quartzite and overlying limestone strata similar to the miogeosynclinal strata in southeast Arizona, southwest New Mexico and northeast Sonora. The southern exposure near the Santa Maria Mine has 500 m of relief.

Mezcalera Basin Western Margin: the Sonora-Sinaloa Transpressional Fault.

The presence of Bisbee Group equivalent strata in the region where Sonora-Chihuahua-Sinaloa join and the continuation of at least 180 km and possibly 400 km south southeast into Sinaloa is problematic. The sandstone, marl and limestone strata strongly correlate with deposition 500 or more km into northern Sonora. The hundreds of meters of mature Lower Cretaceous sandstone above and below the Aptian-Albian carbonate section is inconsistent with the extensive shallow shelf carbonates that continue from the Lampasos, Sonora area (40 km north-northwest of Sahuaripa, Sonora) where it overlaps the marginal basin. All Lower Cretaceous strata covering the Upper Jurassic marginal basin fill, from Sahuaripa south, are thin bedded deep shelf calcareous shale and limestone. There is no evidence that the sand could have been transported across the basin. The only mechanisms to position the sandstones in their current position would be long shore drift along an unobserved shore line or by tectonic transport along a translational structure.

If the correlation is correct, the potential southward migration to this location would have had to occur after deposition of the Bisbee Group. Their present position appears to reflect migration along a transpressional fault consistent with the Cenomanian east-directed thrusting observed in the Cucurpe area (Mauel and others, 2011), in the Sahuaripa, Sonora region (Pubellier and others, 1995) and now documented in the Zataque, Sinaloa and Lluvia del Oro, Chihuahua area. This potential transpressional motion also corresponds to the timing of the thrusting of the Mezcalera overthrust plate on to the platform.

A major transpressional fault appears to separate the Caborca and Cortez Terranes from the marginal Jurassic basin by these terranes overthrusting the basin strata. This fault is documented projecting into the Zataque, Sonora-Sinaloa area where Bisbee equivalent strata are folded and thrust over time equivalent Lower Cretaceous shelf strata as well as Upper Jurassic slope and rise strata. Bisbee Group correlative strata thrust over same aged shelf strata and underly Jurassic basin rise strata in the Gochico, Sonora, Zataque, Sonora-Sinaloa and Lluvia del Oro, Chihuahua areas.

Mezcalera Overthrust.

Mezcalera Group in the Mezcalera thrust plate allows the marginal basin from which it was derived to be observed with greater detail despite the structural disruption. It is within the overthrust allowing better observation of the slope and rise facies of the Mezcalera Group and the transition between the slope and shelf that can be observed such as at Cazadero, Zacatecas (this study) where distal platform carbonate beds project out into laminated calcareous shelf strata.

The best exposed part of the proposed marginal basin is the Mezcalera overthrust that was thrust out of the proposed marginal basin in the Late Cenomanian from north of Parral, Chihuahua to south of Zacatecas, Zacatecas. The age determined from fossils for these slope and rise strata are Late Jurassic through Early Cretaceous (Eguiluz-de Atunano and Campa-Urango, 1982). PEMEX drilling penetrates the thrust plate at various localities with Parral-1 cutting the Mezcalera thrust overlying a section from Middle Jurassic Nazas through a complete Lower Cretaceous section capped with Cenomanian strata (Grajales-Nishimura. and others, 1992).

Durango Inverted Basement Block.

A simple model of attributing the Paleozoic outcrops at Valle de Olivos, Chihuahua (possibly Pan-African Precambrian), Santa Maria del Oro, San Lucas del Ocampo, and Salamandra, Durango to an inverted basement block west of the Mezcalera thrust sheet rather than another terrane does not appear to have been considered in the previously proposed tectonic models (Dickinson and Lawton, 2001). It is described as being metamorphosed by the Ouachita Orogeny from both dates and character of metamorphism but the origin as an accreted terrane or suture zone, the Parral Terrane is generally accepted by the same authors.

Transform Faults.

The lack of evidence for any offset on the western belt of Upper Jurassic strata suggest a serious problem with the proposal of a major post Mid-Jurassic strikeslip fault, the Mojave-Sonora Megashear. It has been argued that this left lateral fault of 800 to 1,000 km of displacement cuts across into the interior of Mexico and across to the Gulf of Mexico. The belt of the same black marine shale that produces Upper Jurassic ages where dated clearly crosses the proposed fault without obvious offset.

The Mojave-Sonora Megashear is often proposed as a mechanism to allow structural compensation for the overlap modeled between the Mexican craton and Gondwana crust during the construction of Pangea (Sedlock and others, 1993; Dickenson and Lawton, 2001). Dickinson and Lawton (2001) proposed the California-Coahuila Transform that is similar to the proposed Middle Jurassic Mojave-Sonora Megashear (Anderson and Schmidt, 1983), but they proposed that initial movement was in the Permian and Triassic with later Jurassic movement. The original definition of an offset as indicated by Pb isotopes on the north boundary of Caborca does not conflict with the proposed model of a transpressional fault moving south southeast down the coast from the segment fault segment originally defined.

Although this study has not observed evidence for the major movement proposed (Dickenson and Lawton, 2001; Anderson and others, 2005a; Jones and others, 1995), it is entirely possible that significant adjustment has occurred along a large number of fractures cutting across the Mexican craton rather than one large one to compensate for the overlap of Mexico with Gondwana indicated by various Pangea reconstructions. This may explain the abundant different sub-parallel fault zones that have been proposed to be cutting east southeast across the Mexican craton (Anderson and Schmidt, 1983; Molina-Garza and Iriondo, 2007). With a relatively weak tongue of crust resisting the significant subduction or rifting forces pushing against Mexico since the Triassic, adjustment along many much smaller faults might accomplish the same result of shifting the Mexican craton to adjust for the overlap modeled between Gondwana and Mexico.

Naming of the Marginal Basin: The Mezcalera Marginal Basin.

A final issue for discussion is the name for the proposed marginal basin and contained strata. South of Batopilas the basin has been called the Guerrero Terrane (Campa and Coney, 1983) with later generally unsuccessful attempts to change the original terrane nomenclature to Tahue (Sedlock and others, 1993) and the approach of using both names (Dickinson and Lawton, 2001). The Guerrero Province (in place deposition as opposed to accreted) or Guerrero Marginal Basin would be appropriate as locational names as there is widely accepted association of Guerrero with the region encompassing the southern part of the proposed basin. The main problem is that Guerrero will probably always be associated with the accreted terrane model.

The Mezcalera name was originally proposed for the Upper Jurassic and Lower Cretaceous strata northeast of Parral by PEMEX geologist Araujo-Mendieta, and Arenas-Partida (1986) for the same strata already named the Parral Formation in the Parral District. The Mezcalera name has become widely adopted by SGM publications and broader literature (Dickinson and Lawton, 2001) as the Mezcalera Thrust and the combined Mezcalera Group with various formational subdivisions including the Mezcalera Formation. Depending where it is sampled, it produces fossil ages from Late Jurassic through Early Cretaceous. Deformed Cretaceous detritus off of the thrust (Indidura and Caracol) are attributed to being part of the thrust sheet. Another name, evolved in the mineral industry, for the Upper Jurassic-Lower Cretaceous Mezcalera is the Parral-Proaño Group combined from Parral Formation in the Parral District and Proaño Formation in the Fresnillo District. There is now a conflicting name with the Parral Terrane, but that conflict is artificial because the so-called Parral Terrane (Dickinson and Lawton, 2001) is more likely an inverted fault block of the Ouachita age basement of central Mexico. Dickinson and Lawton (2001) proposed an oceanic plate named the Mezcalera as the source for the Mezcalera Group that is separate from the accreted Guerrero Terrane. The least complex model for the Moris crustal fragment and the Rusias (Rio Fuerte Group of Mullen, 1978) and Arteaga subterranes (Centeno-Garcia and others, 1993) is that they are remnants of the extended crustal rifted margin. The Parral Terrane is applied to a belt of Paleozoic metasediments More nomenclature problems arise when we consider the possible extension of the marginal basin into the possible Cucurpe basin and the Papago Terrane of Haxel and others (1980).

The two most viable names from the existing literature appear to be Guerrero or Mezcalera. The Guerrero name is the most established, but its long association with the accretionary model may prove difficult to transition into a marginal basin model. The

Mezcalera is a well-established name for the overthrust found from north of Parral, Durango to south of Zacatecas, Zacatecas and although has not been referred to as a marginal basin, it was proposed for modeling and subdividing purposes and for these reasons is a better name. If we remove the second subduction zone proposed by Dickinson and Lawton (2001) that produces no known arc magmatism, their Mezcalera Ocean Basin becomes a marginal or back arc basin as proposed here. The Mezcalera Basin strata have been thrust, onto the craton (the Mezcalera Overthrust) making it the source basin and the best fit for an existing name to apply to this proposed marginal basin. On the issue of marginal vs. back arc basin, the Mezcalera Basin spent the first approximate 55 Ma as a marginal and forearc basin and the second 50 Ma as a back arc basin.

Summary.

This belt of Jurassic marine and volcanic strata with sparse outcrops of Precambrian and Paleozoic underlying crust are interpreted here as a marginal basin formed by rifting initiated between the end of the Permian construction of Pangea and the end of the Late Triassic. This marginal basin filled with continental deposits through the Middle Jurassic before marine flooding in the Middle to Late Jurassic.

The Precambrian through Paleozoic crustal fragments found encased in the Upper Jurassic marine strata are interpreted as high standing blocks on an extended crustal floor from the adjacent cratonic crust to the east. The more brittle metamorphic Precambrian blocks from Moris, Chihuahua stood high above basin floor. The much younger Paleozoic crust southwest of Batopilas with lower grade Late Paleozoic metamorphism deformed much more, producing more, less pronounced fragments west of the Paleozoic crust of central Mexico under the extended basin floor.

Evidence for the crossing of these Upper Jurassic basin fill strata by the proposed Mojave-Sonora Megashear (MSM) is not documented in the literature nor is it observed in the field. Either it does not exist or it is covered by Tertiary volcanic rocks. Indistinguishable outcrops of Upper Jurassic strata are now documented to cross through the supposed MSM trace without any observable disruption beyond the east-directed tectonic shortening. No evidence of a Late Paleozoic (Coahuila-Tamaulipas Transform of Dickinson and Lawton, 2001) through Middle Jurassic (MSM, of Silver and Anderson, 1974) transform motion cutting or controlling the boundaries of the proposed marginal basin has been observed. Instead there is stronger evidence of transpressional motion along the west side of the marginal basin in the Late Cenomanian with thrusting of Caborca basement and supracrustal strata over Late Cenomanian through Lower Jurassic basin strata.

The proposed trace of the transpressional fault is marked by this thrusting of the Caborca Terrane over the Jurassic and Lower Cretaceous basin strata from the northern border of Sonora, through the western side of the Cucurpe Basin on to Sahuaripa and Arivechi. The presence of kilometers of sandstone similar to the Morita and Cintura bounding a rudisted bearing limestone and marl similar to the Mural Formation (all of the Bisbee Group) crops out at Lluvia del Oro, Chihuahua; Zataque, Sinaloa-Sonora and Magistral, Sinaloa starting just north of the junction of Sonora, Chihuahua and Sinaloa. This suggest that the marine shelf margin upon which the Lower Cretaceous strata were deposited either had to project much further to the south than the presently known Bisbee Basin or that the emplacement of the Caborca Terrane at the end of the Cenomanian occurred along a transpressional fault partially paralleling Mexico's west coast.

At the Zataque and Lluvia del Oro area, it is interpreted that the western distal edge of the Bisbee Group has been transported south then thrust over both the Lower Cretaceous slope and rise strata as well as the Upper Jurassic basin fill.

A large amount of evidence including lithology and ages indicates that the Upper Jurassic-Lower Cretaceous Mezcalera Group that was thrust onto the craton is derived from the rise and slope deposits of the Mezcalera rifted marginal basin. The Late Cenomanian timing of the Mezcalera thrust indicated in Parral-1 is consistent with the thrusting of Caborca Paleozoic strata and Precambrian basement on to the Upper Jurassic and Lower Cretaceous Bisbee Group of the marginal basin. Further evidence of timing of the thrusting are the carbonate debris flows, containing fragments very characteristic of the extensive Aptian-Albian platform carbonates and found within the Upper Cenomanian through Turonian Indidura Formation at Salamandra, Durango along the margin of the proposed Durango Inverted Basement Block.

CONCLUSIONS: MARGINAL BASIN TECTONIC EVOLUTION

New mapping at Moris, Batopilas, and Lluvia del Oro, Chihuahua and Zataque, Sonora-Sinaloa along with new U-Pb dates on detrital and igneous samples at Batopilas, Chihuahua along with more dispersed U-Pb dating at Arizpe, Sonora; Moris, Chihuahua; and Zataque, Sonora-Sinaloa, all integrated with existing mapping and dating presents an opportunity to re-evaluate existing tectonic models for the region. The addition of the Batopilas Upper Jurassic marine strata by a U-Pb age (149 Ma) on the submarine volcanism helps fill a gap in the string of known occurrences that parallel Mexico’s northwest continental crust.

It is proposed that a west coast marginal basin existed in Mexico from at least the Jurassic through the Early Cretaceous and was subjected to arc migration first sweeping westward across the marginal basin to an position west of the basin followed by a return sweep to the east into the well documented Late Cretaceous through Cenozoic arc migration (Damon and others, 1981; Clark and others, 1982). The new U-Pb dating at Batopilas documents the proposed migration of the arc through the area. The 149 Ma date fills in a gap in the arc migration model. The dating of the Nazas to the east suggests that younger dates are developing to the west and the Batopilas date confirms this. Following this Late Jurassic age, the arc may have continued to migrate to the west to position itself as the Early Cretaceous Alisitos Arc. The Alisitos Arc is out of the study area to the west but two new U-Pb dates at Arizpe (124 Ma) in northern Sonora and a single date at Zataque on a distal tuffs (138 Ma) in the Bisbee Group Morita Formation indicate the Alisitos was erupting to the west during the Early Cretaceous (see Fig. 3.49). Additional new U-Pb dates (88 to 85 Ma) in the Batopilas District document the return sweep of the Tarahumara arc during the Early Late Cretaceous Cenomanian and Turonian. A single date on an igneous rock at Batopilas documents the last gasp of Laramide volcanism until it returns in the Eocene with the Dolores Diorite stock (55 Ma) and the Satevo Rhyodacite Flow (46 Ma).

Complex models of continental crossing transform faults such as the Sonora-Mojave Megashear (Anderson and others, 2005) or the California-Coahuila Transform (Dickinson and Lawton, 2001) appear unnecessary with the new and compiled data. While no evidence of these transform faults was observed in the area defined as a marginal basin, outcrops of a major strike slip fault was observed south of Chanate (Chn on Fig. 3.48) in the northern part of Sonora. This fault is consistent with the original definition of the Sonora Mojave Megashear that was based on Pb isotopes. The issue is does it cross the proposed marginal basin or does it turn south southeast parallel to the present coast. Most evidence of a transform fault crossing northern Mexico is not well supported and if the basement is all Ouachita age as proposed here, there appears to be no offset.

The final major issue is the Guerrero Accretion model. If the Pacific margin arc is sweeping across the proposed marginal basin, the progression of the arc across the basin should follow a systematic pattern. The sweeping pattern appears to be developing even with the limited number of U-Pb dates that have been obtained during the study. Some of the complexities of the region attributed to arc accretion might well be the result of transpressional motion along the coast. It is not denied that some accretion occurred within the Guerrero Province, while the extent of evidence for the marginal Basin would suggest accretion is a minor component. This study has sought to understand apparent differences between the various terranes or provinces while seeking to understand possible relationships that might tie the various elements together as related provinces than dividing them into disparate accreted terranes.

Upper Jurassic marine slope and rise strata exposed in deep canyons cutting the Sierra Madre Occidental Volcanic Province (SMOVP) were mapped during this study at the newly recognized occurrence at Batopilas as well as the known exposures at Moris, Chihuahua. Remapping has provided key evidence to interpret the region as a large Mesozoic basin marginal to the Mexican Precambrian through Paleozoic basement, herein termed the Mezcalera Marginal Basin. The earliest deposition seen in the basin is the Lower to Middle Jurassic continental strata that filled the developing rift, in the south central Arizona "Papago Terrane" and the Cucurpe Basin of north central Sonora, both of which have no known Pre-Jurassic autochthonous crust. Upper Jurassic fossiliferous marine and tuffaceous strata were known to cap the Lower and Middle Jurassic continental deposits in a belt from Cucurpe, Nacozari and Arivechi, Sonora on to Moris and El Pilar, Chihuahua. Now based on this mapping and dating on Batopilas, Chihuahua where it enters the domain of the previously proposed Guerrero Terrane (Fig. 3.27). Similar appearing strata from Topia and Bacis, Durango and Rosario, Sinaloa have published paleontological ages from Middle to Upper Jurassic ammonites and appear to continue these marginal basin deposits to well within the interior of the proposed Guerrero Terrane. Compatible radiometric dates have been obtained from Cucurpe and Batopilas.

In northern Sonora, the Lower Cretaceous Bisbee Group strata cap the Upper Jurassic Cucurpe Formation of the marginal basin marine strata. In southern Sonora, thin bedded calcareous slope deposits replace the Bisbee Group as the Lower Cretaceous strata and continue at least as far south as Chirimoyo, Durango.

In northern Sonora this basin is bound on the east side by the North American craton that acts as a buttress against which the basin fill later deformed. Isoclinal folding of the Mural limestone is documented in Sierra Bellotal, south southeast of Cananea, and in the Middle Jurassic Lily Formation in Sierra Purica and Cobriza, west of Nacozari. The structural edge of the North American craton passes between these folds and Cananea and Nacozari, Sonora; and although it is buried by SMOVP to the south of Nacozari, the interpretation of magnetic fabric (Fig. 2.8) suggests its continuation to the south southeast into southern Mexico.

The west side of the basin is well documented, showing that the Precambrian and Paleozoic of the Caborca Terrane was thrust, during the Cenomanian, out over the Upper Jurassic and Lower Cretaceous basin fill from the Arizona border to the Sahuaripa, Sonora area. In the Sahuaripa and nearby Arivechi, Sonora areas the basin fill becomes pinched between the North America basement and Caborca basement, producing intense deformation including thrusts and overturned folds in the basin fill, but no evidence of a major transvers structure such as the previously proposed Mojave-Sonora Megashear cutting the basin was observed. One hundred kilometers southeast of Arivechi, in the Moris, Chihuahua region an irregular basin floor of Precambrian and Paleozoic crust crops out within the Upper Jurassic strata. The newly recognized Upper Jurassic strata at Batopilas contains abundant ammonites, belemnites, submarine flow domes and explosive volcanic debris dated at 149 Ma (U-Pb).

The marginal basin exhibits evidence of a Late Triassic to Early Jurassic rifting with the Triassic rift basalts of the San Francisco gneiss west of Lower Paleozoic basement blocks at Rio Fuerte and San Jose de Gracias, Sinaloa and possibly Morelos, Chihuahua. Onlapping of the rugged basement blocks at Moris by the accumulating Jurassic marine strata is documented by exclusively Precambrian detrital zircon dates from sandstones in strata paleontologically dated as Late Jurassic (Garcia-Cortez and others, 2000; Herrera-Galvan and Cabañas-Villalba, 2004). This rugged buried topography is what would be expected in an environment of extended crust. The presence of Paleozoic crustal blocks between the Francisco Gneiss and the Paleozoic basement to the east further support a model of extended crust for the floor of the marginal basin.

In the Cucurpe area, the Basomori Formation (Lower Jurassic) and San Martin Formation (Middle Jurassic) are continental strata (Mauel and others, 2011) that fill the rift basin of this model. Marine deposition began as the Late Jurassic Cucurpe Formation filled the basin. If the Guerrero Terrane strata are in fact marginal basin deposits on the flank of the Mexican craton, it would more properly be classified as a province rather than a terrane.

The basin deposits transition between the Papago Terrane of south-central Arizona to the Cucurpe Basin of Lawton and others (2003) with Arivechi, Sonora, Moris, Chihuahua and Batopilas, Chihuahua on into Durango. New geologic data along the west coast of Mexico presented here points toward a less complex model of tectonic development, very different from the current tectonic models for Mexico's west coast. Rather than arc accretion creating a Guerrero Terrane along the west coast that terminates at a major transcurrent fault, the MSM (Mojave-Sonora Megashear), cutting across the Paleozoic Ouachita basement of Mexico, the geology indicates a rift-derived marginal basin continuing uninterrupted from southwest Arizona (Papago Terrane) north of the Cucurpe Sub-Basin in north central Sonora to the south southeast across the proposed MSM through the Arivechi area to Moris, Chihuahua and at least as far as Batopilas, Chihuahua. Intracratonic grabens, subparallel to the rifted western margin, display a stronger structural affinity between the intracratonic basins and this rifted western margin than they do with the Gulf of Mexico. The often proposed relationship between these intracratonic basins and the Gulf of Mexico while synchronous with the western rifting reflect almost perpendicular orientation between structures generated by the two events.

The major eastward thrusting of the Caborca Terrane over the Mezcalera Marginal Basin strata in the Late Cenomanian and the concurrent thrusting of the same marginal basin strata onto the Paleozoic crust of central Mexico as the Mezcalera Overthrust is substantial evidence that the southward migration of the Caborca basement block along a major transpressional fault early in the Late Cretaceous is a viable model for the tectonics and timing for this event. The precise nature of the Alisitos Arc prior to the southward migration of the Caborca Terrane is difficult to model particularly without direct knowledge of Baja California, but the presence of Alisitos age tuffs in the Morita Formation in northeast Sonora and the Morita Formation equivalent along the Sonora-Sinaloa border suggest the Alisitos Arc was located west of the Mezcalera Marginal Basin.

The timing of Caborca's emplacement combined with the eastward sweep of the arc suggests that it was related to a major plate margin event such as the overriding of a spreading ridge or as previously proposed the collision with an oceanic arc. Such an event resulted in triggering faster, flatter subduction and the resulting Upper Cretaceous through Eocene eastward migration of the magmatic arc. The Mid-Jurassic Nazas Arc swept from north central Mexico westward through the Cucurpe-Batopilas region where it is documented as Late Jurassic on to the Baja California Alisitos Arc position during the Early Cretaceous. The arc then migrated back to the east emplacing the Sonora-Sinaloa Batholith in Sonora and Sinaloa early in the Late Cretaceous before sweeping across Mexico in the well documented migration of the arc to deposit the Eocene volcanic rocks of the Big Bend area and eastern Mexico (Damon and others, 1981). Finally the arc swept back to the west at the end of the Eocene initiating the Sierra Madre Occidental Volcanic Field with Eocene silicic flows before the great Oligocene and Miocene rhyolitic welded tuff-dominated eruptions. A Mesozoic volcanic arc sweeping across Mexico explains the observed distribution of magmatic activity with much less complexity than accreted arcs and subduction reversals.

Possible rifting of the western margin of the Mexican craton is suggested in the Late Triassic, as evidenced by the Francisco Gneiss, after the completion of the construction of Pangea at the beginning of the Triassic. Extended Precambrian and Paleozoic crust was spread across the floor of the basin, as documented at Moris and Morelos, Chihuahua and Rio Fuerte and San Jose de Gracias, Sinaloa. Continental volcanic, clastic and minor lagoonal strata initially began filling the basin in the Early to Middle Jurassic as seen in south central Arizona "Papago Terrane" and Cucurpe Basin in Sonora.

Rather than an actual splitting of continental crust into segments, it appears that extension from the rolling back of the plate resulting from slow subduction might have created a strong enough extensional environment to actually create the intracratonic basins of Mexico and the marginal basin. The alignment of these basins is more suggestive of developing three parallel extensional basins rather than forming as right lateral pull-apart basins as suggested for the similarly timed Chihuahua Basin (Haenggi and Muehlberger, 2005).

In the Middle to Late Jurassic the marginal basin was flooded and began filling with debris from submarine volcanoes, turbidites from the adjacent platform and fossiliferous marine shale. The andesitic to dacitic arc volcanism migrated west into the marginal basin from the Nazas Arc position on the craton during the Late Jurassic. The basin continued to fill through the Early Cretaceous but was represented by two distinct sedimentation facies: the Bisbee Group ranging from alluvial fans, reworked high bed load deltas and a shelf reef and lagoonal complex at the Aptian-Albian boundary, that developed on a major drainage system discharging from the North American craton into southeast Arizona, New Mexico and northern Sonora and spilled into the marginal basin. South of the delta complex the Lower Cretaceous consists of thin bedded deep shelf strata. The volcanic arc continued to migrate westward out of the study area during the Lower Cretaceous to the position referred to as the Alisitos Arc. The only evidence of the Alisitos in the study area are distal silicic tuffs in the Morita Formation dated at 136 Ma at Zataque to 124 Ma at Arizpe, Sonora (Hauterivian to basal Aptian). Late in the Cenomanian a change in the interaction between North American crust and the oceanic plate (Farallon?) introduced a significant lateral force along with a major increase in the subduction rate of the oceanic plate along the continental margin. This more rapid subduction greatly increased the compressive force along the Mexican craton boundary and flattened the subducting plate and initiated the migration of the volcanic arc eastward until it reached West Texas in the Eocene. This change in plate interactions resulted in the migration of the Caborca and Cortez basement blocks along a major transpressional fault from southern California into northwest Sonora and the northwestern coast of Mexico south, producing a repeated section of two segments of the Mexican coast in southwestern Mexico. Increased shortening along the transpressional fault thrust Caborca, Cortez and the former northwest coast of Mexico over the marginal basin strata shortened the width of the basin and forced the Mezcalera thrust plate on to the platform of less buoyant Paleozoic crust of Mexico’s Central Highlands. Continued shortening in the Turonian inverted basement blocks along the craton margin and erosion of these inverted blocks separated the thrust sheet from the marginal basin to the west. Shortening continued to the east in the intracratonic basins well into the Eocene producing folds in the Eocene volcanic rocks.

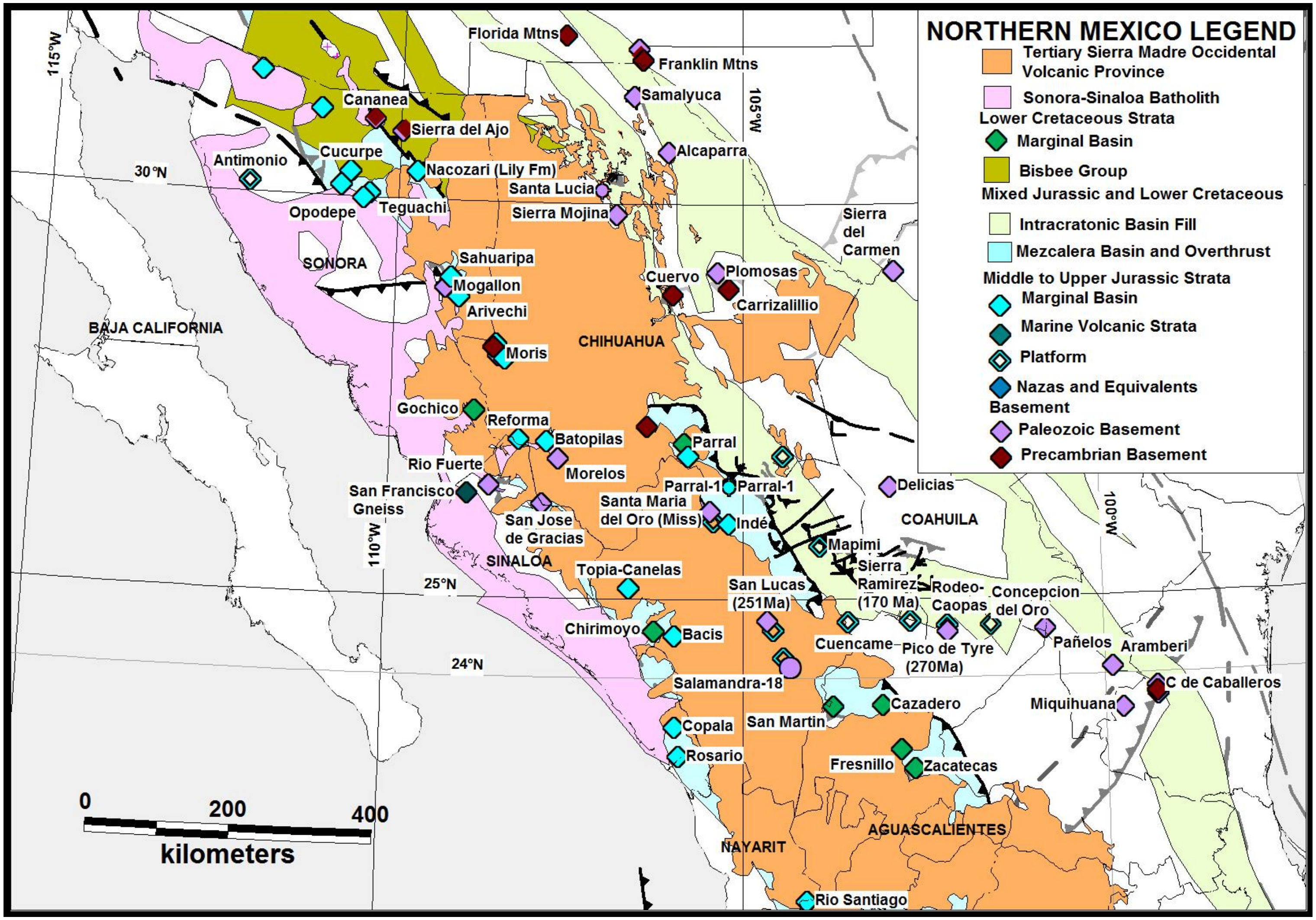
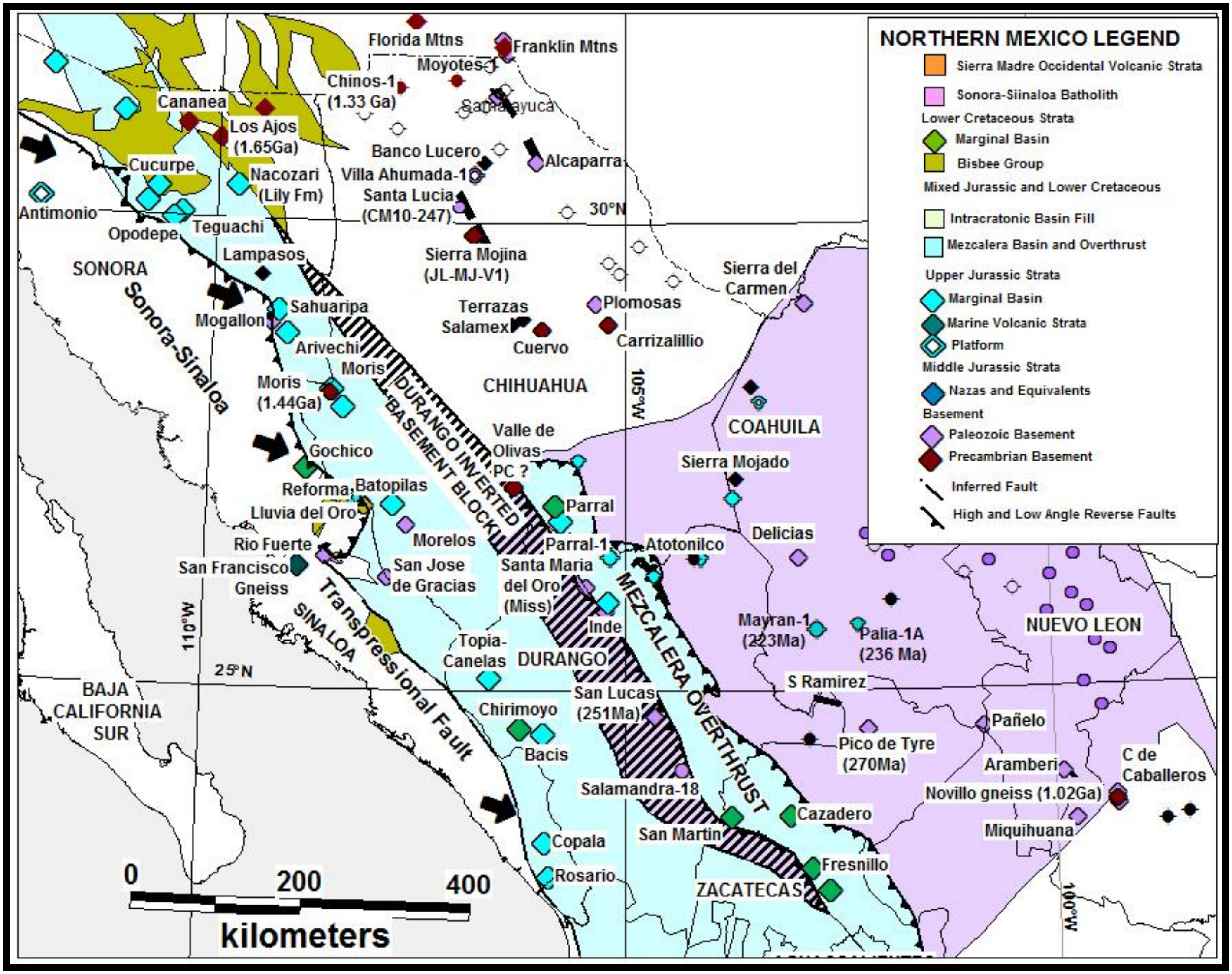

NORTHERN MEXICO LEGEND
Tertiary Sierra Madre Occidental Volcanic Province
Sonora-Sinaloa Batholith
Lower Cretaceous Strata
Marginal Basin
Bisbee Group
Mixed Jurassic and Lower Cretaceous
Intracratonic Basin Fill
Mezcalera Basin and Overthrust
Middle to Upper Jurassic Strata
Marginal Basin
Marine Volcanic Strata
Platform
Nazas and Equivalents
Basement
Paleozoic Basement
Precambrian Basement
115°W
110°W
105°W
100°W
30°N
25°N
24°N
BAJA CALIFORNIA
SONORA
CHIHUAHUA
COAHUILA
SINALOA
NAYARIT
AGUASCALIENTES
Florida Mtns
Franklin Mtns
Samalyuca
Alcaparra
Cananea
Sierra del Ajo
Cucurpe
Antimonio
Nacozari (Lily Fm)
Santa Lucia
Opodepe
Teguachi
Sierra Mojina
Sierra del Carmen
Sahuaripa
Mogallon
Arivechi
Cuervo
Plomosas
Carrizalillio
Moris
Gochico
Reforma
Batopilas
Parral
Morelos
Rio Fuerte
San Francisco Gneiss
Parral-1
Parral-1
Santa Maria del Oro (Miss)
Indé
Delicias
San Jose de Gracias
Mapimi
Sierra Ramirez (170 Ma)
Rodeo-Caopas
Concepcion del Oro
Topia-Canelas
San Lucas (251Ma)
Chirimoyo
Bacis
Cuencame
Pico de Tyre (270Ma)
Pañelos
Aramberi
Salamandra-18
C de Caballeros
Miquihuana
Cazadero
San Martin
Copala
Rosario
Fresnillo
Zacatecas
Rio Santiago
0
200
400
kilometers

Figure 3.1

Figure 3.1 Generalized geologic provinces with defining outcrops of northern Mexico compiled from the author's mapping, and references discussed in the text.

Map shows outcrops important to the proposed tectonic model For the marginal basin model most outcrops occur around the margins of and in the floors of canyons incised into the Sierra Madre Occidental Volcanic Province and roof pendants in the Sonora-Sinaloa Batholith.

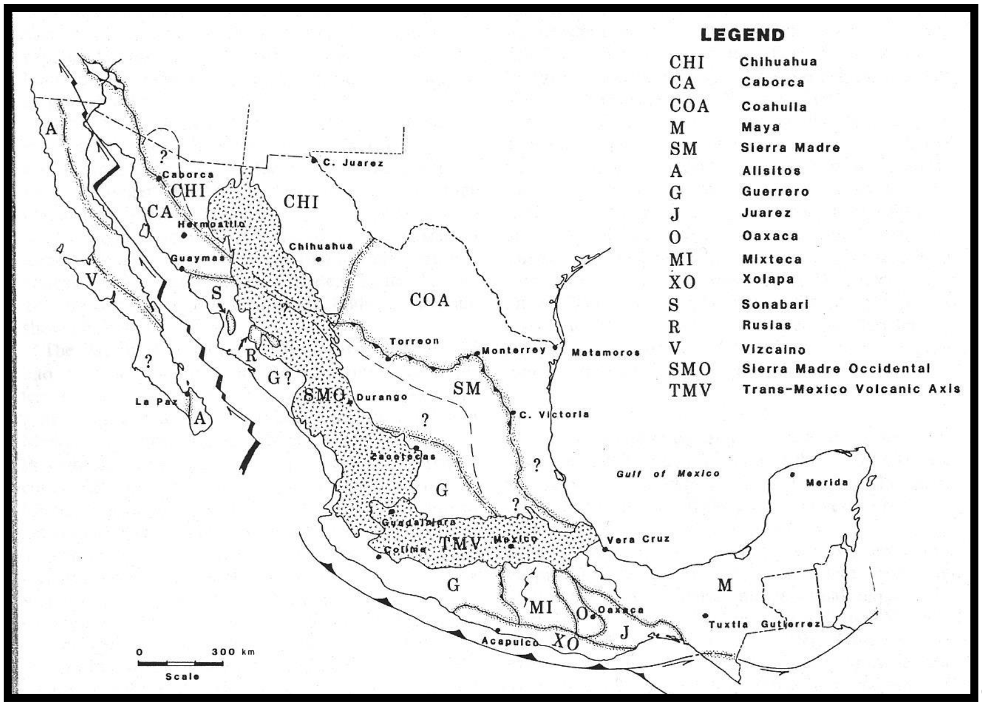


NORTHERN MEXICO LEGEND
Sierra Madre Occidental Volcanic Strata
Sonora-Siinaloa Batholith
Lower Cretaceous Strata
Marginal Basin
Bisbee Group
Mixed Jurassic and Lower Cretaceous
Intracratonic Basin Fill
Mezcalera Basin and Overthrust
Upper Jurassic Strata
Marginal Basin
Marine Volcanic Strata
Platform
Middle Jurassic Strata
Nazas and Equivalents
Basement
Paleozoic Basement
Precambrian Basement
Inferred Fault
High and Low Angle Reverse Faults
Florida Mtns
Franklin Mtns
Moyotes-1
Chinos-1
(1.33 Ga)
Cananea
Los Ajos
(1.65Ga)
Banco Lucero
Villa Ahumada-1
Alcaparra
Santa Lucia
(CM10-247)
30°N
Cucurpe
Nacozari
(Lily Fm)
Antimonio
Opodepe
Teguachi
Lampasos
Sierra Mojina
(JL-MJ-V1)
SONORA
Sonora-Sinaloa
Sahuaripa
Mogallon
Arivechi
Terrazas
Salamex
Cuervo
Plomosas
Carrizalillio
Sierra del
Carmen
Moris
Moris
(1.44Ga)
CHIHUAHUA
105°W
DURANGO INVERTED
BASEMENT BLOCK
COAHUILA
Gochico
Valle de
Olivas
PC ?
Sierra Mojado
Reforma
Batopilas
Lluvia del Oro
Parral
Morelos
Rio Fuerte
Parral-1
Atotonilco
Delicias
San Francisco
Gneiss
San Jose
de Gracias
Santa Maria
del Oro
(Miss)
Inde
MEZCALERA OVERTHRUST
110°W
SINALOA
Transpressional Fault
Mayran-1
(223Ma)
Palia-1A
(236 Ma)
NUEVO LEON
Topia-
Canelas
DURANGO
25°N
BAJA
CALIFORNIA
SUR
San Lucas
(251Ma)
S Ramirez
Chirimoyo
Bacis
Pañelo
Pico de Tyre
(270Ma)
Aramberi
C de
Caballeros
Salamandra-18
Novillo gneiss (1.02Ga)
Cazadero
San Martin
Miquihuana
Copala
Fresnillo
0
200
400
Rosario
ZACATECAS
100°W
kilometers

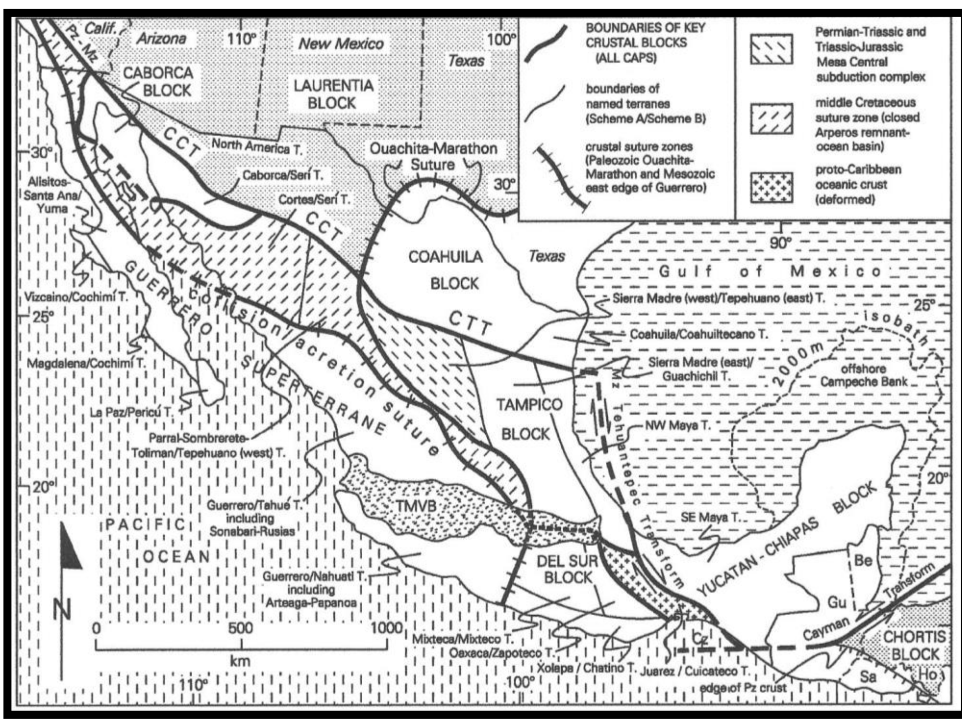
Figure 3.2

Figure 3.2 Interpreted geologic map of Mezcalera Basin from this study. As Fig. 3.1 without the SMOVP and Sonora-Sinaloa Batholith.

Map is compiled from field observations made during this study. Deletion of the Sierra Madre Occidental Volcanic Province (SMOVP) and Sonora-Sinaloa batholith as map layers allows for the interpretation of the possible distribution for the proposed marginal basin. The boundary of the Durango Inverted Basement Block is mostly inferred but is well delineated as a high angle reverse fault along its margin with the Mezcalera Overthrust at Indé and drill hole Salamandra-18. Elevations of ~2,000 m at Indé and Salamandra-18 are well above the elevations of Jurassic strata found in the basin at Moris (~1,5000 m) and at Batopilas (~1,000 m). The Paleozoic basement is inverted in relation to both the Mezcalera Basin and Overthrust.



(a)



(b)

Figure 3.3 Mexico’s tectonic terranes as interpreted by (a) Campa and Coney (1983) and (b) Dickinson and Lawton (2001).

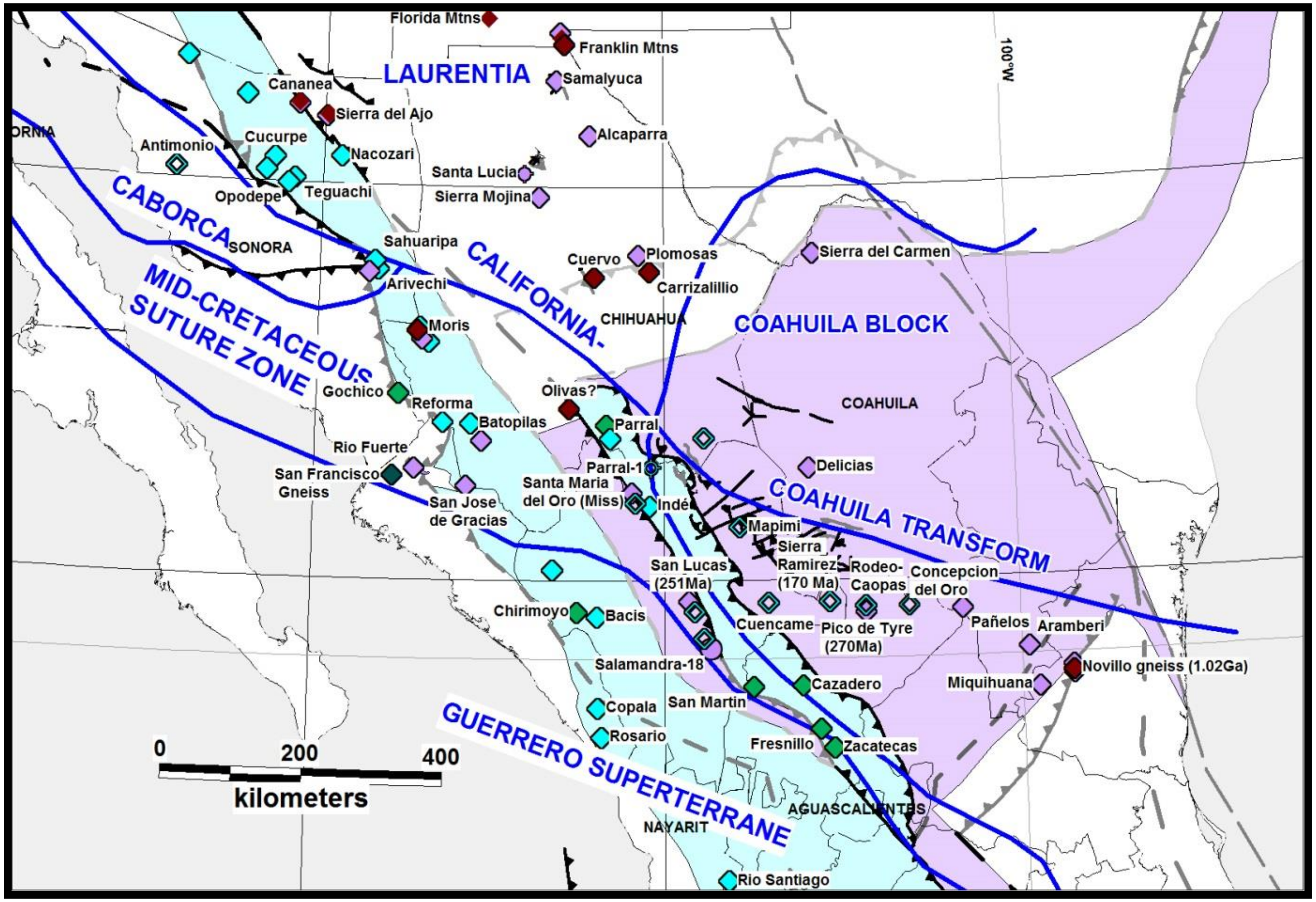

Florida Mtns
Franklin Mtns
LAURENTIA
Samalyuca
Cananea
Sierra del Ajo
Alcaparra
Antimonio
Cucurpe
Nacozari
Santa Lucia
Opodepe
Teguachi
Sierra Mojina
CABORCA
SONORA
Sahuaripa
CALIFORNIA-
Cuervo
Plomosas
Sierra del Carmen
Carrizalillio
Arivechi
MID-CRETACEOUS
SUTURE ZONE
CHIHUAHUA
COAHUILA BLOCK
Moris
Gochico
Reforma
Olivas?
Parral
COAHUILA
Batopilas
Rio Fuerte
Parral-1
Delicias
San Francisco
Gneiss
Santa Maria
del Oro (Miss)
Indé
COAHUILA TRANSFORM
San Jose
de Gracias
Mapimi
Sierra
Ramirez
(170 Ma)
Rodeo-
Caopas
Concepcion
del Oro
San Lucas
(251Ma)
Chirimoyo
Bacis
Cuencame
Pico de Tyre
(270Ma)
Pañelos
Aramberi
Salamandra-18
Novillo gneiss (1.02Ga)
Cazadero
Miquihuana
Copala
San Martin
GUERRERO SUPERTERRANE
Rosario
Fresnillo
Zacatecas
0
200
400
kilometers
AGUASCALIENTES
NAYARIT
Rio Santiago
100°W

Figure 3.4

Figure 3.4 The major tectonic boundaries of Dickinson and Lawton (2001) overlain in blue over the interpreted marginal basin and overthrust of this study.

The main belt of Jurassic turbidites interpreted to delineate the Mezcalera Basin (light blue) crosses the Laurentian Craton, the Mid-Cretaceous suture zone and into a substantial portion of the Guerrero Superterrane. Paleozoic schist basement (purple) is exposed within the Mid-Cretaceous Suture Zone and the Jurassic Nazas tuffs resting on the Paleozoic schist at Indé and Salamandra-18 indicate that it is part of the adjacent basement to the east not sutured to Mexico in the Mid-Cretaceous.

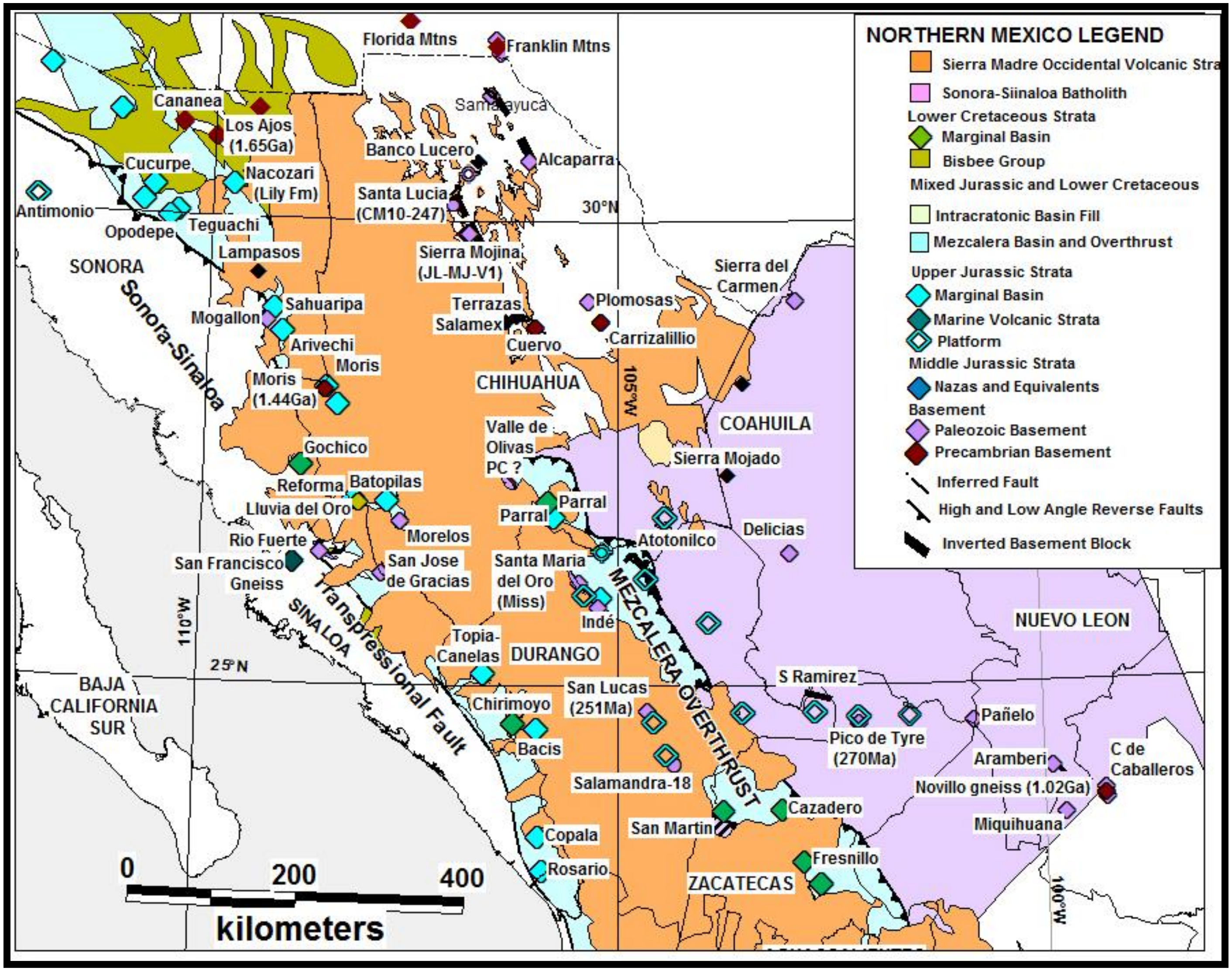

NORTHERN MEXICO LEGEND
Sierra Madre Occidental Volcanic Stra
Sonora-Siinaloa Batholith
Lower Cretaceous Strata
Marginal Basin
Bisbee Group
Mixed Jurassic and Lower Cretaceous
Intracratonic Basin Fill
Mezcalera Basin and Overthrust
Upper Jurassic Strata
Marginal Basin
Marine Volcanic Strata
Platform
Middle Jurassic Strata
Nazas and Equivalents
Basement
Paleozoic Basement
Precambrian Basement
Inferred Fault
High and Low Angle Reverse Faults
Inverted Basement Block
Florida Mtns
Franklin Mtns
Samalayuca
Cananea
Los Ajos
(1.65Ga)
Banco Lucero
Alcaparra
Cucurpe
Nacozari
(Lily Fm)
Santa Lucia
(CM10-247)
Antimonio
30°N
Opodepe
Teguachi
Lampasos
Sierra Mojina
(JL-MJ-V1)
SONORA
Sonora-Sinaloa
Sierra del
Carmen
Sahuaripa
Plomosas
Mogallon
Terrazas
Salamex
Carrizalillio
Cuervo
Arivechi
Moris
Moris
(1.44Ga)
CHIHUAHUA
105°W
COAHUILA
Gochico
Valle de
Olivas
PC ?
Sierra Mojado
Reforma
Batopilas
Lluvia del Oro
Parral
Parral
Delicias
Rio Fuerte
Morelos
Atotonilco
San Francisco
Gneiss
San Jose
de Gracias
Santa Maria
del Oro
(Miss)
Transpressional Fault
SINALOA
MEZCALERA OVERTHRUST
110°W
Indé
NUEVO LEON
25°N
Topia-
Canelas
DURANGO
BAJA
CALIFORNIA
SUR
S Ramirez
San Lucas
(251Ma)
Chirimoyo
Pañelo
Pico de Tyre
(270Ma)
Bacis
Aramberi
C de
Caballeros
Salamandra-18
Novillo gneiss (1.02Ga)
Cazadero
San Martin
Miquihuana
Copala
Fresnillo
0
200
400
Rosario
ZACATECAS
100°W
kilometers

Figure 3.5

Figure 3.5 The Late Jurassic through Early Cretaceous marginal basin is defined by isolated exposures within the SMOVP usually found in canyon floors.

Exposures are found at Rosario, Copala, Chirimoyo, Bacis, Topia, Batopilas, north of Reforma, Moris and Arivechi. Marginal basin strata were thrust onto the Mexican craton from Parral to southern Zacatecas by a Late Cenomanian shortening event.

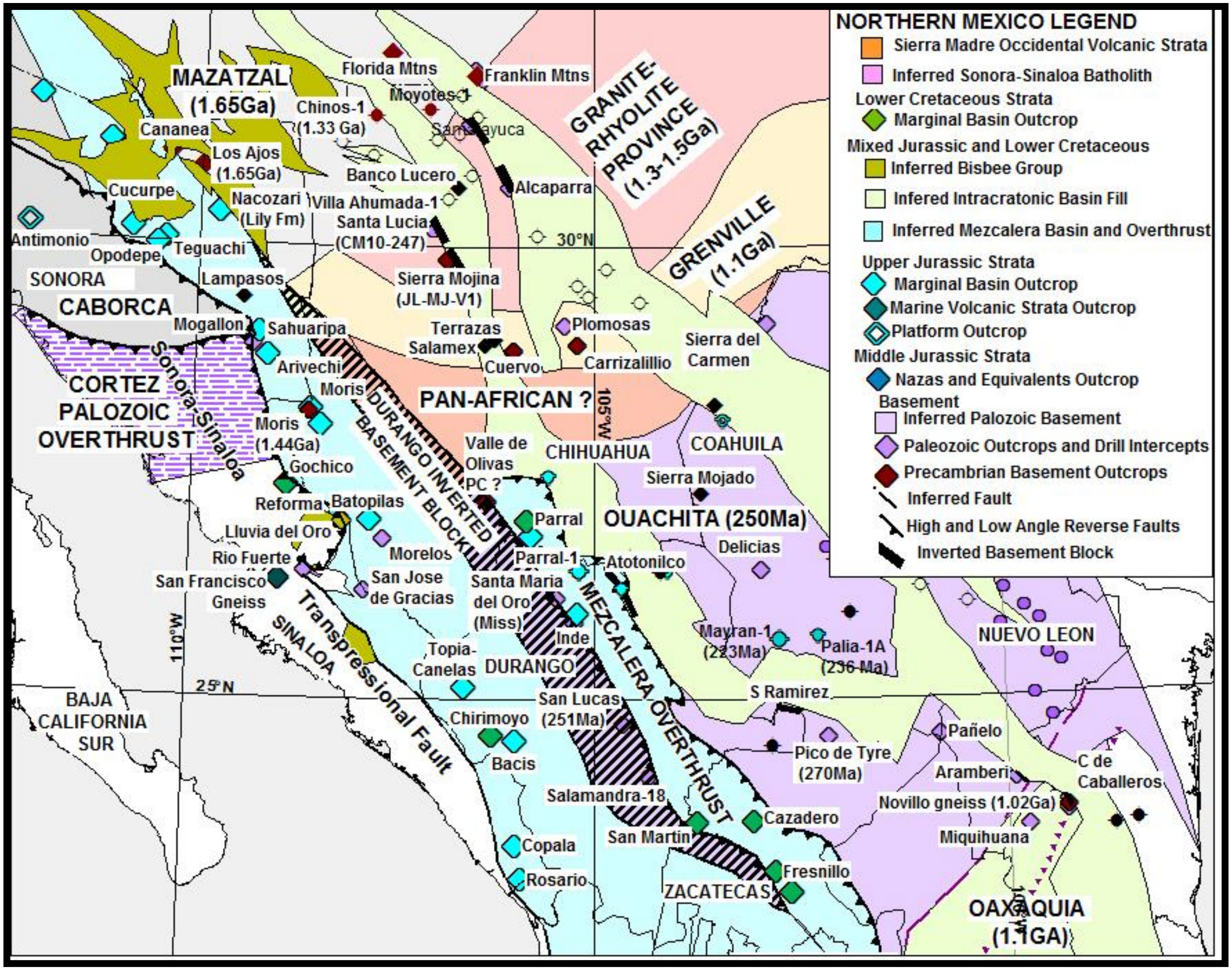

NORTHERN MEXICO LEGEND
Sierra Madre Occidental Volcanic Strata
Inferred Sonora-Sinaloa Batholith
Lower Cretaceous Strata
Marginal Basin Outcrop
Mixed Jurassic and Lower Cretaceous
Inferred Bisbee Group
Infered Intracratonic Basin Fill
Inferred Mezcalera Basin and Overthrust
Upper Jurassic Strata
Marginal Basin Outcrop
Marine Volcanic Strata Outcrop
Platform Outcrop
Middle Jurassic Strata
Nazas and Equivalents Outcrop
Basement
Inferred Palozoic Basement
Paleozoic Outcrops and Drill Intercepts
Precambrian Basement Outcrops
Inferred Fault
High and Low Angle Reverse Faults
Inverted Basement Block
MAZATZAL (1.65Ga)
GRANITE-RHYOLITE PROVINCE (1.3-1.5Ga)
GRENVILLE (1.1Ga)
PAN-AFRICAN ?
OUACHITA (250Ma)
CORTEZ PALOZOIC OVERTHRUST
DURANGO INVERTED BASEMENT BLOCK
MEZCALERA OVERTHRUST
Sonora-Sinaloa
SINALOA Transpressional Fault
OAXAQUIA (1.1GA)
SONORA
CABORCA
CHIHUAHUA
COAHUILA
NUEVO LEON
DURANGO
ZACATECAS
BAJA CALIFORNIA SUR
Florida Mtns
Franklin Mtns
Moyotes-1
Chinos-1 (1.33 Ga)
Samalayuca
Cananea
Los Ajos (1.65Ga)
Banco Lucero
Alcaparra
Cucurpe
Nacozari (Lily Fm)
Villa Ahumada-1
Santa Lucia (CM10-247)
Antimonio
Opodepe
Teguachi
30°N
Lampasos
Sierra Mojina (JL-MJ-V1)
Mogallon
Sahuaripa
Terrazas
Salamex
Cuervo
Plomosas
Carrizalillio
Sierra del Carmen
Arivechi
Moris
105°W
Moris (1.44Ga)
Gochico
Valle de Olivas PC ?
Sierra Mojado
Reforma
Batopilas
Parral
Lluvia del Oro
Morelos
Parral-1
Atotonilco
Delicias
Rio Fuerte
San Francisco Gneiss
San Jose de Gracias
Santa Maria del Oro (Miss)
Inde
Mayran-1 (223Ma)
Palia-1A (236 Ma)
110°W
Topia-Canelas
25°N
San Lucas (251Ma)
S Ramirez
Chirimoyo
Bacis
Pañelo
Pico de Tyre (270Ma)
Aramberi
C de Caballeros
Salamandra-18
Novillo gneiss (1.02Ga)
Cazadero
San Martin
Miquihuana
Copala
Fresnillo
Rosario

Figure 3.6

Figure 3.6 Northern Mexico with interpreted basement tectonic elements beneath the Sierra Madre Occidental Volcanic Province and Mesozoic cover.

The Paleozoic and older basement to the Mexican basins is also shown. Map primarily based on the mapping of this study supplemented by published studies discussed in the text. Basement provinces labeled on map.

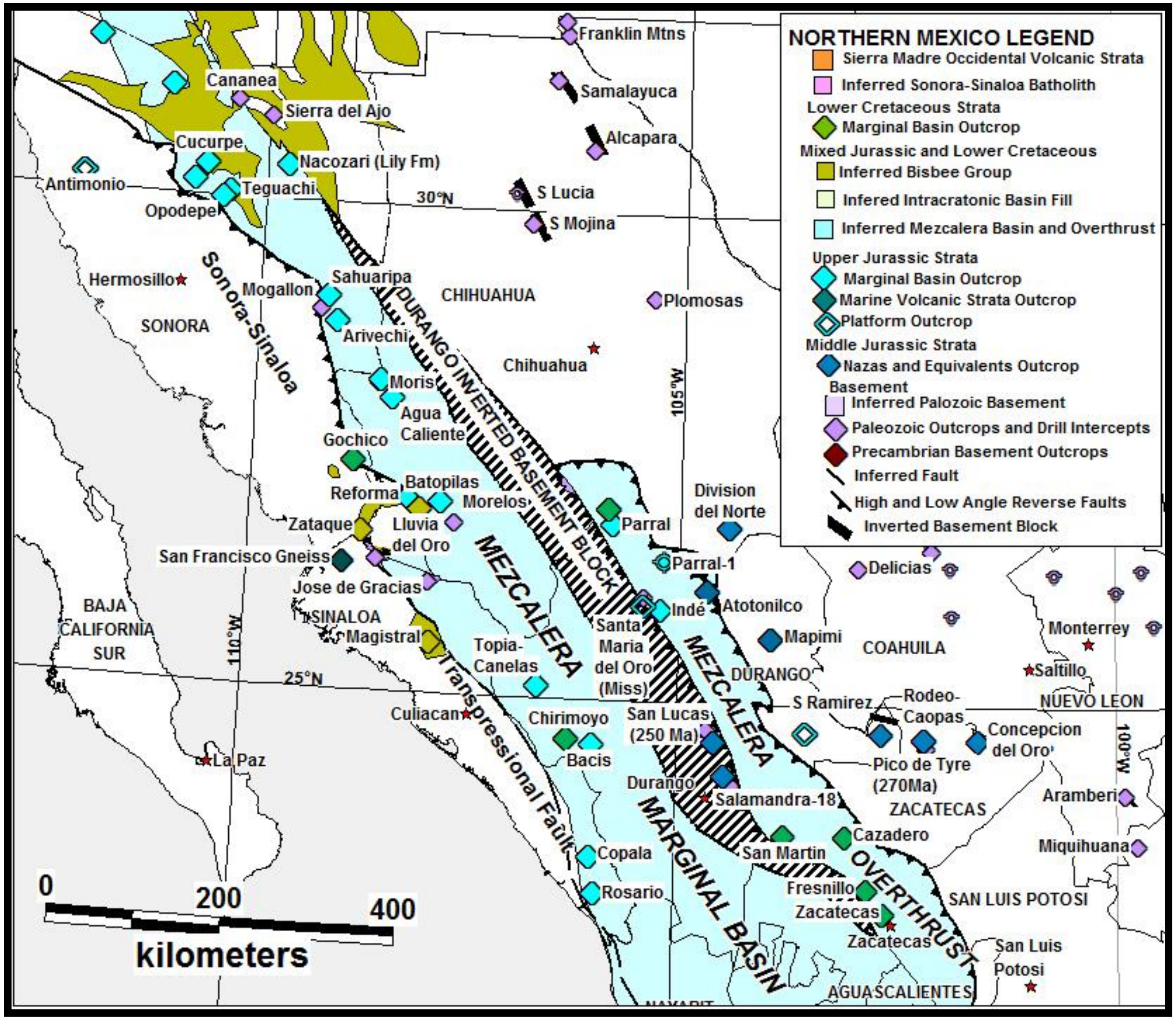

NORTHERN MEXICO LEGEND
Sierra Madre Occidental Volcanic Strata
Inferred Sonora-Sinaloa Batholith
Lower Cretaceous Strata
Marginal Basin Outcrop
Mixed Jurassic and Lower Cretaceous
Inferred Bisbee Group
Infered Intracratonic Basin Fill
Inferred Mezcalera Basin and Overthrust
Upper Jurassic Strata
Marginal Basin Outcrop
Marine Volcanic Strata Outcrop
Platform Outcrop
Middle Jurassic Strata
Nazas and Equivalents Outcrop
Basement
Inferred Palozoic Basement
Paleozoic Outcrops and Drill Intercepts
Precambrian Basement Outcrops
Inferred Fault
High and Low Angle Reverse Faults
Inverted Basement Block
DURANGO INVERTED BASEMENT BLOCK
MEZCALERA
MEZCALERA
MARGINAL BASIN
OVERTHRUST
Sonora-Sinaloa
Transpressional Fault
SONORA
CHIHUAHUA
COAHUILA
DURANGO
NUEVO LEON
ZACATECAS
SAN LUIS POTOSI
AGUASCALIENTES
SINALOA
BAJA CALIFORNIA SUR
30°N
25°N
110°W
105°W
100°W
Franklin Mtns
Samalayuca
Alcapara
S Lucia
S Mojina
Plomosas
Chihuahua
Cananea
Sierra del Ajo
Cucurpe
Nacozari (Lily Fm)
Antimonio
Teguachi
Opodepe
Hermosillo
Mogallon
Sahuaripa
Arivechi
Moris
Agua Caliente
Gochico
Batopilas
Reforma
Morelos
Zataque
Lluvia del Oro
San Francisco Gneiss
Jose de Gracias
Magistral
Topia-Canelas
Culiacan
La Paz
Chirimoyo
Bacis
Copala
Rosario
Parral
Division del Norte
Parral-1
Indé
Atotonilco
Santa Maria del Oro (Miss)
Mapimi
S Ramirez
San Lucas (250 Ma)
Durango
Salamandra-18
San Martin
Fresnillo
Zacatecas
Zacatecas
Cazadero
Rodeo-Caopas
Pico de Tyre (270Ma)
Concepcion del Oro
Delicias
Monterrey
Saltillo
Aramberi
Miquihuana
San Luis Potosi
0
200
400
kilometers

Figure 3.7

Figure 3.7 Map highlights the outcrops (diamonds) important to the marginal basin model interpreted from this study of northern Mexico.

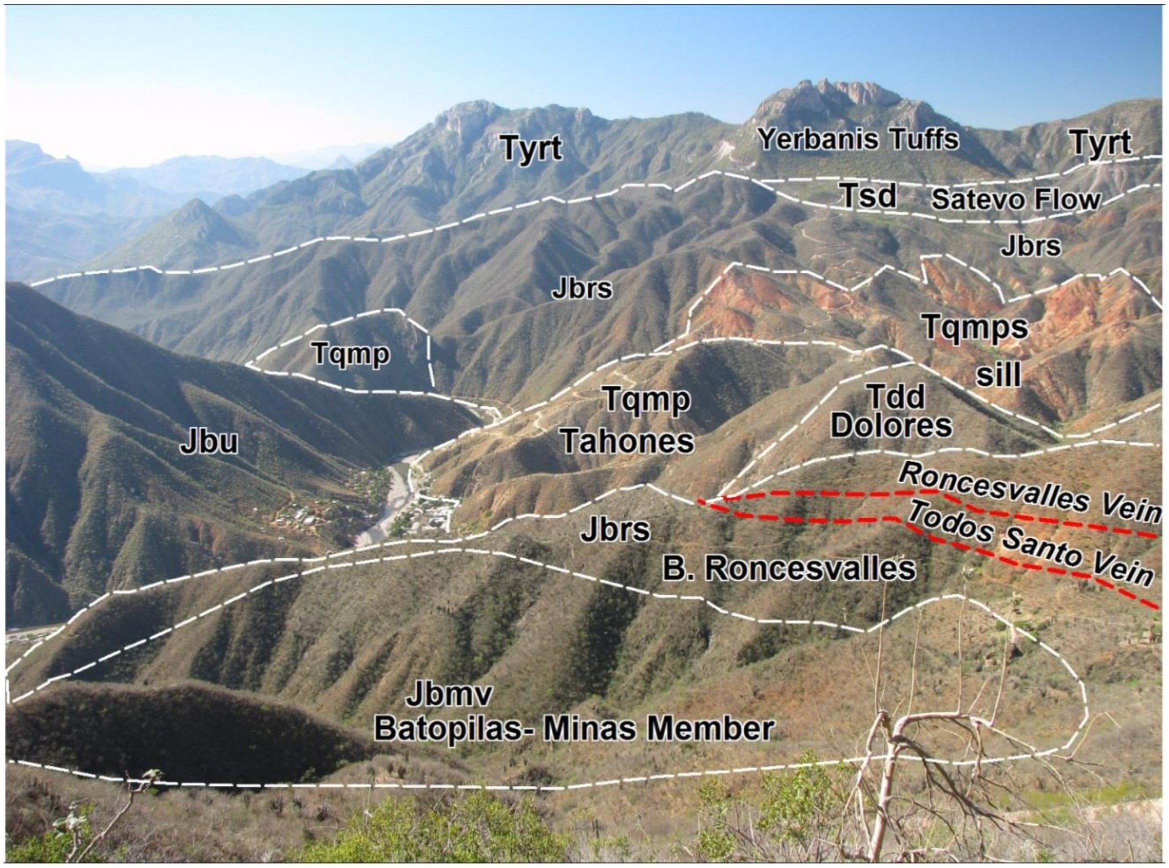


Figure 3.8 Overview of the Batopilas Silver District looking south from Animas Ridge with geology superimposed.

Important volcanic and sedimentary strata, and igneous bodies in the photo include Jbmv-Batopilas Formation Minas Member flow dome, Jbrs-Batopilas Formation Roncesvalles Member Marine strata, Kqmps- Tahonas quartz monzonite porphyry, Tdd-Dolores diorite, Tsd- Satevo Rhyodacite, Tyrt- Yerbanis rhyolite tuffs, Tyrf- Yerbanis rhyolite flow. Also shown in red is the surface trace of two major veins the Roncesvalles and the Todos Santos. Photo taken south southwest from NAD 27 Mexico Zone 12, 228,169E, 2,994,585N on crest of Animas Ridge (shown on Fig. 3.15).

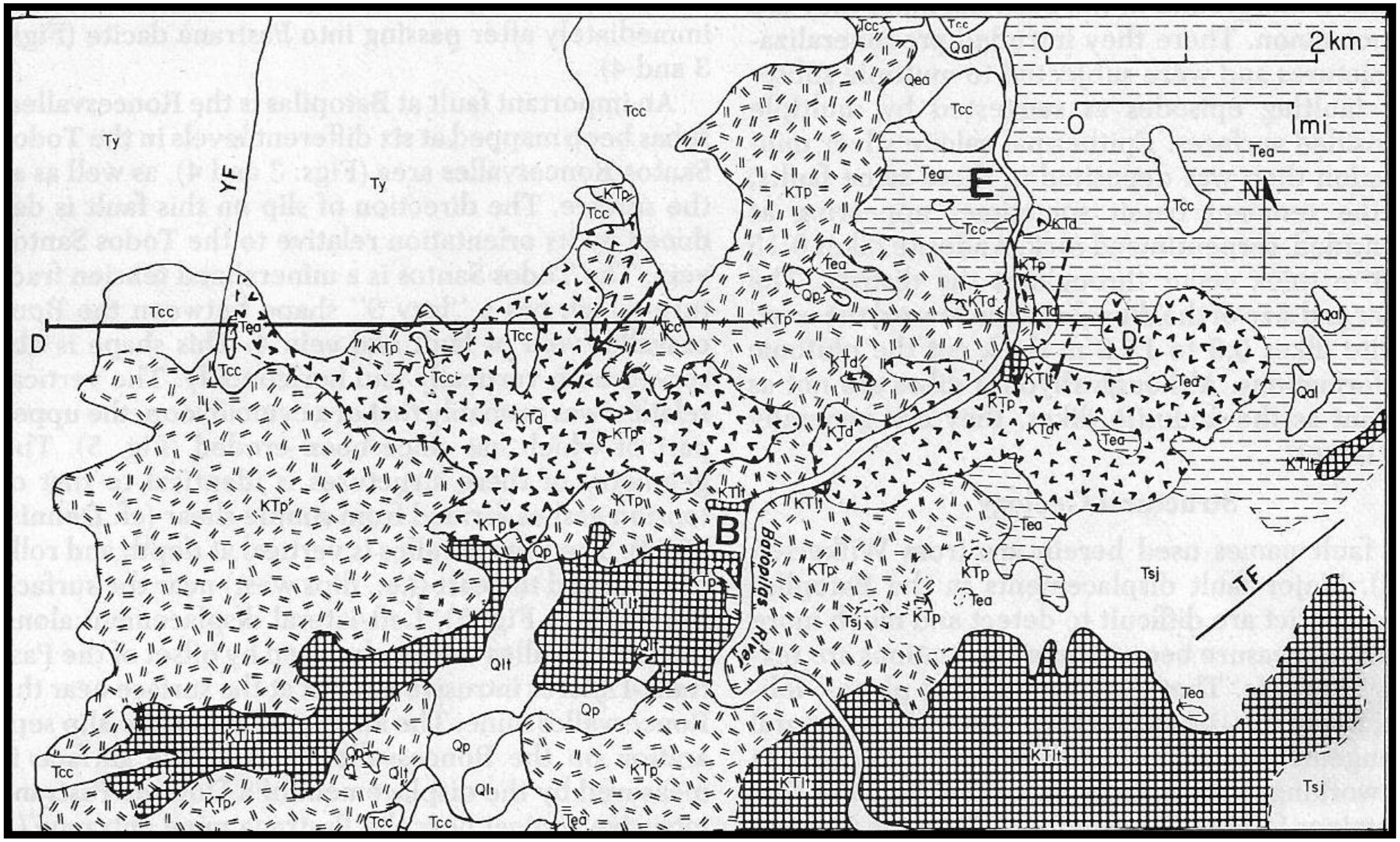


Figure 3.9 Geologic map of the Batopilas District by Wilkerson and others (1988).

They concluded that the Pastrana Dacite, equivalent to the Batopilas Formation of this study, is the oldest unit, the Dolores Diorite the second oldest unit, followed by the Tahonas granodiorite. Their Tsj and Tea units are both flow breccias mapped as Tarahumara in this study. The only other major unit is the Ty Yerbanis rhyolite tuffs of Oligocene age.

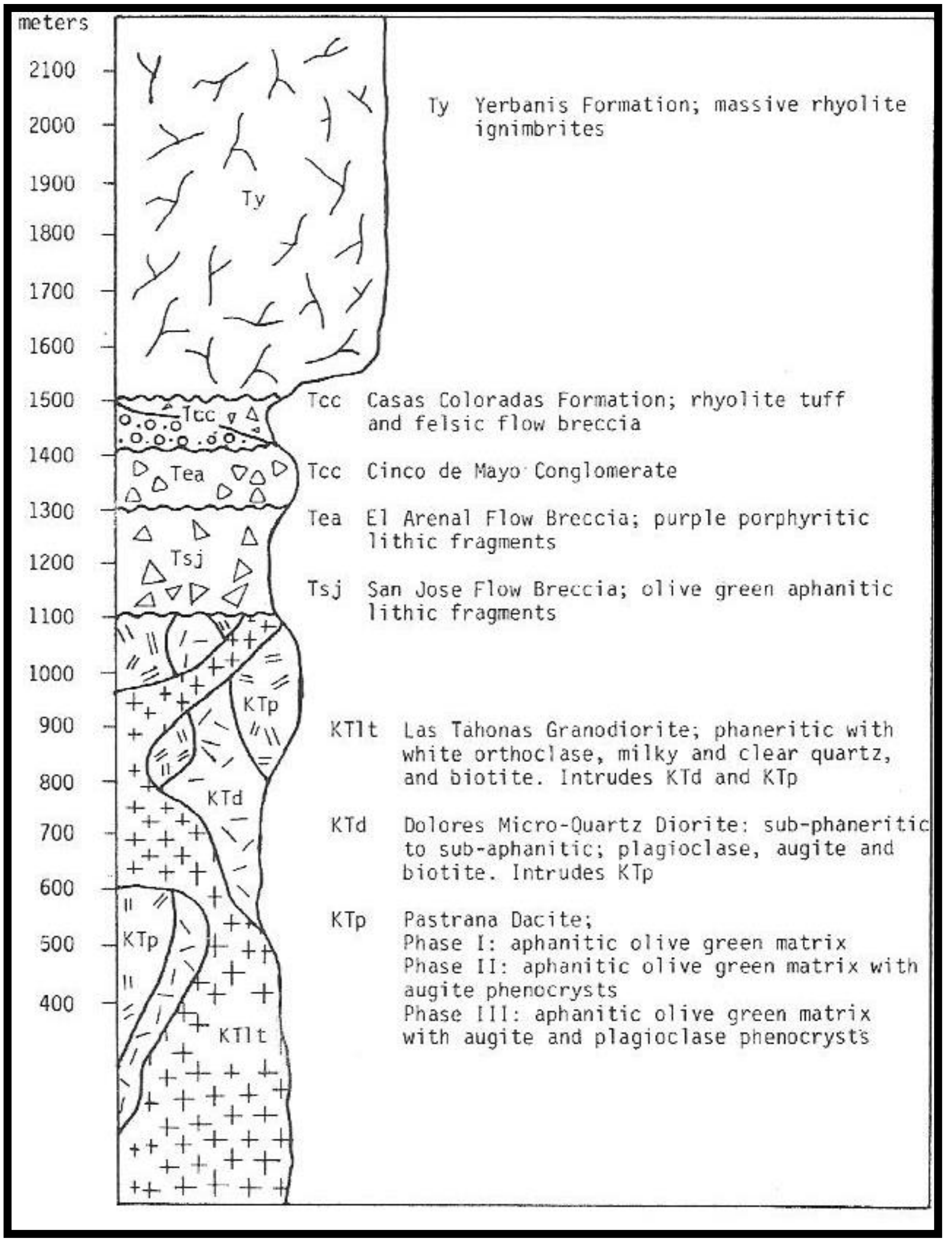


Figure 3.10 Diagrammatic stratigraphic section of Wilkerson and others (1988).

U-Pb dating of the different units for this study yielded indirectly a Jurassic date of 149 Ma for the renamed Minas Member of the Bolaños Formation (Pastrana Dacite of Wilkerson), a middle Upper Cretaceous date of 85 Ma on the Tahonas Granodiorite and confirmed the Lower Eocene date of 55 Ma for the Dolores Biotite-Diorite. The San Jose and Arenal Flow Breccias are both cut by Tahonas age stocks and are mapped in this study as Upper Cretaceous Tarahumara Formation.

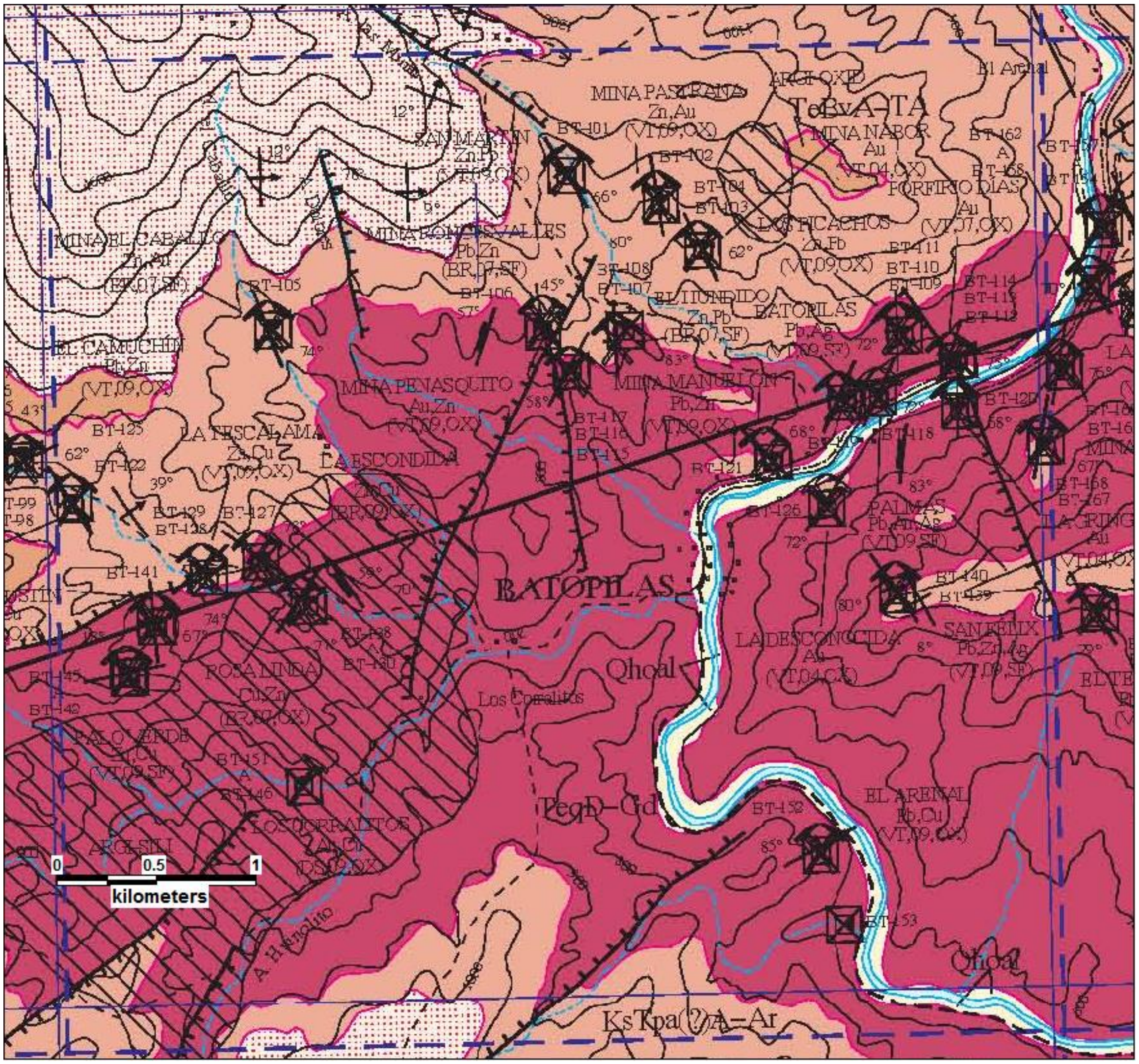


Figure 3.11 The Servicio Geologico Mexicano Batopilas G13-A41 1:50k scale geologic quadrangle map of the Batopilas District.

The core of the district is mapped as a purple Eocene quartzdiorite to granodiorite Te qD-Gd (attributed to Minera Cascabel, 2001 but is not the data in their files). The flesh colored unit is KsTpa?A-Ar is mapped as an Upper Cretaceous-Paleocene andesite and sandstone. The 2 offset grids are 5km with the solid blue lines ITRF92 and the dashed blue lines are NAD27 which is still the system used in the mineral industry in Mexico to avoid converting all old mineral surveys to the newer system. ITRF92 solid blue grid Easting 225,000 to 230,000 and Northing 2,990,000 to 2,995,000.

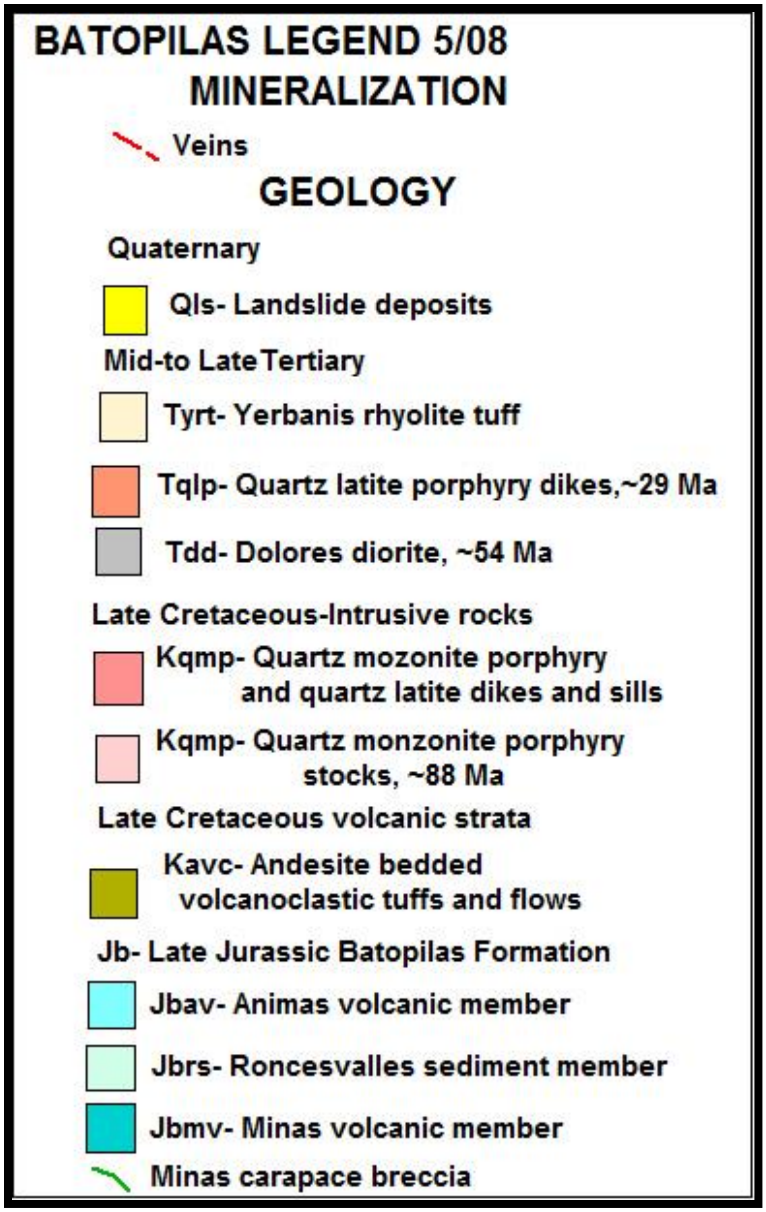


Figure 3.12 Legend for the maps and cross sections of the Batopilas District.

The oldest strata consists of the Upper Jurassic Batopilas Formation with its three members Roncesvalles strata (Jbrs), the Minas volcanic member (Jbmv), and the upper Animas volcanic member (Jbav). Dikes of the same apparent age (Jbd) are found cutting all three members. The Late Cretaceous Tarahumara andesitic volcanic rocks (Kavc) overlie the Batopilas Formation. An important difference between the Batopilas and the Tarahumara is the folding and west-directed thrusting in the Batopilas while the Tarahumara dips to the east without any apparent shortening.

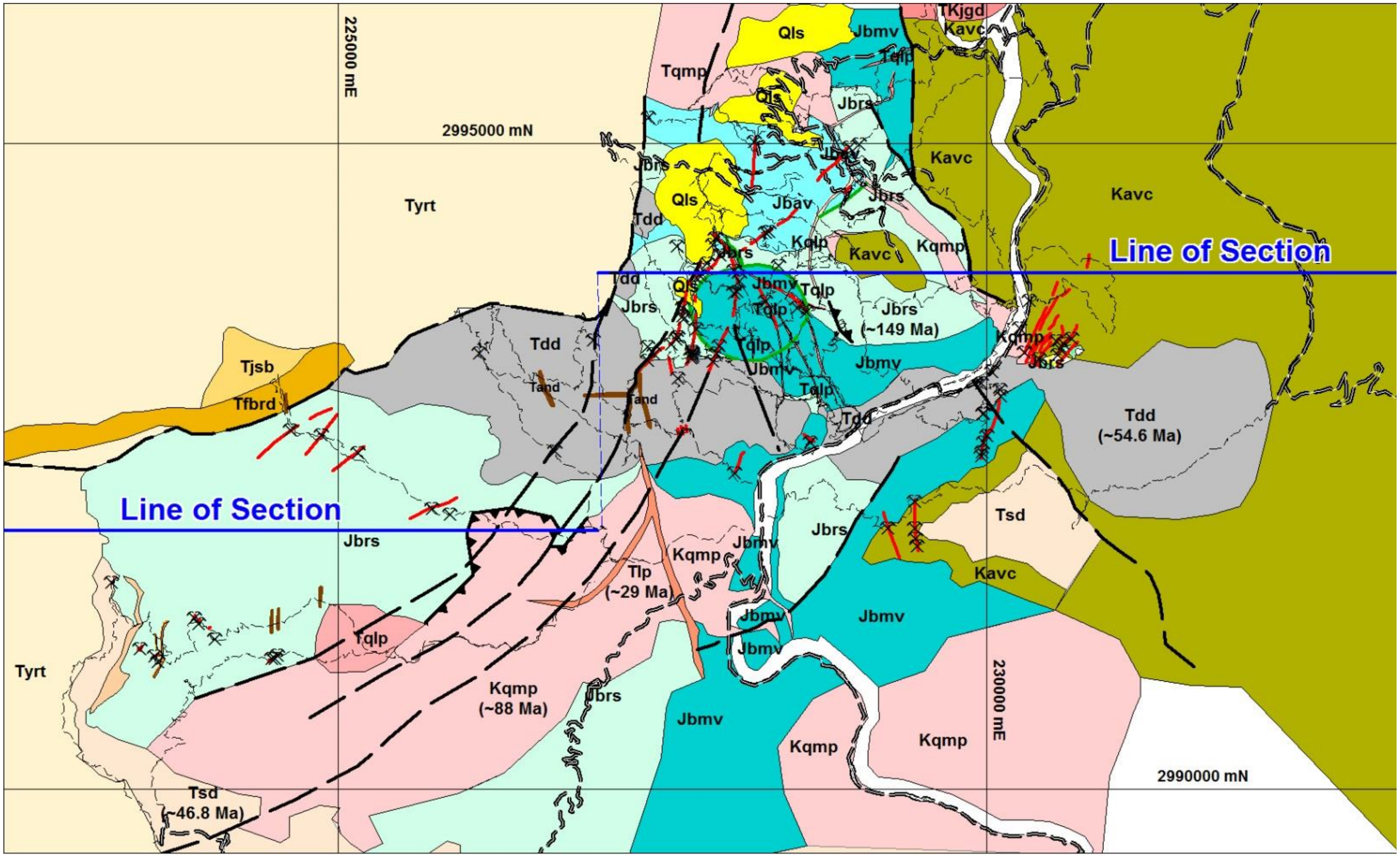

225000 mE
2995000 mN
Tyrt
Qls
Jbmv
TKjgd
Kavc
Tqmp
Tqlp
Jbrs
Kavc
Jbav
Tdd
Kqlp
Kqmp
Line of Section
Tdd
Jbrs
Jbmv
Tqlp
Jbrs
(~149 Ma)
Tjsb
Tfbrd
Tand
Tdd
(~54.6 Ma)
Line of Section
Jbrs
Kqmp
Tlp
(~29 Ma)
Tsd
Tqlp
Tyrt
Kqmp
(~88 Ma)
Jbmv
230000 mE
2990000 mN
Tsd
(~46.8 Ma)

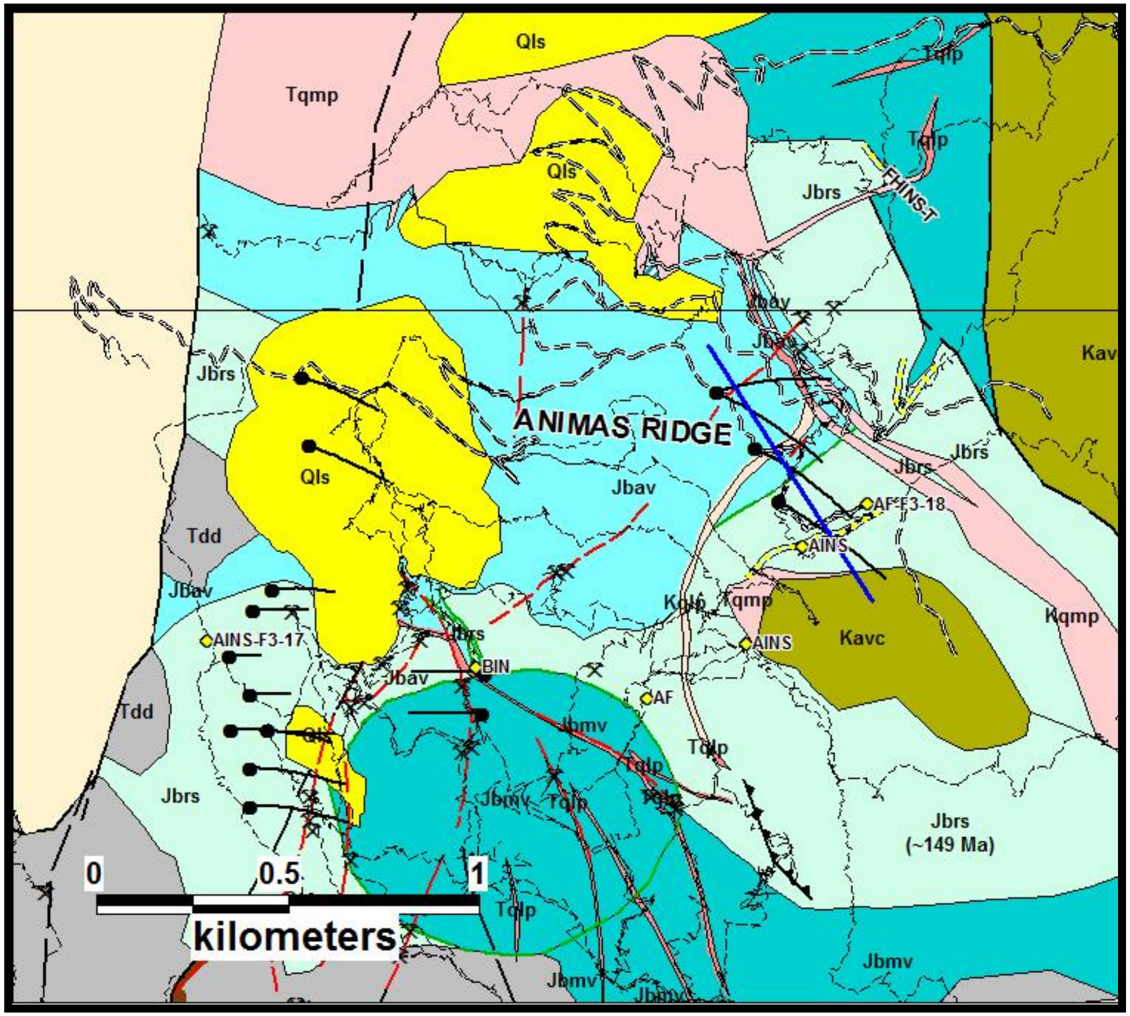
Figure 3.13

Figure 3.13 Batopilas District geology map produced during this study.

Key features other than stratigraphy include arcuate faults that may relate to caldera doming which cross from the central to southwest part of the map and Tjsb which are brecciated Batopilas strata interpreted to relate to caldera venting. A north-northwest normal fault separates the Batopilas Formation (Jb) from most of the Tarahumara Formation (Kavc). A ring structure surrounds the central vent area of the Minas (Jbmv) submarine volcanic rocks. A radial distribution of both Tahonas age dikes and the silver veins of Batopilas is apparent in the central part of the district. The grid is a 1 km UTM NAD 27 Mexico zone 13. See Fig. 3.12 for Legend.

Figure 3.14 Laminated pelagic shale of the Roncesvalles Member of the Batopilas Formation.

Photo was taken on the south flank of Animas Hill. Location NAD 27 Zone13 Mexico 228,666E, 2,994,246N. Hammer is 38 cm long.



Qls
Tqmp
Tqlp
Jbrs
FHINS-T
Kav
ANIMAS RIDGE
Jbav
Tdd
AF-F3-18
AINS
AINS-F3-17
BIN
AF
Kavc
Kqmp
Jbmv
Jbrs
(~149 Ma)
0
0.5
1
kilometers

Figure 3.15

Figure 3.15 Fossil and drill hole localities of the northeast part of the district.

The dotted yellow line represents fossil rich beds, with the yellow dots representing some of the specific ammonite and belemnite localities. Black dots with lines are exploration drill holes projected to the surface and the blue line at the east end of Animas ridge is cross section in Figure 3.22. See Fig. 3.12 for legend.

Figure 3.16 Oriented belemnite fragments in Roncesvalles Member turbiditic carbonate sandstone.

Strata observed in v-shaped outcrop north of AF-F3-18 Belemnites are oriented approximately east-west in outcrop. Sample from 27.0505N, 107.7296W, (UTM NAD 27 zone 13; 228,397E 2,994,970N).

Figure 3.17 Nerinia gastropods exposed in the northeast corner of map (Fig. 3.15) at locality FHINS-T.

Westerly orientation of the elongate fossils suggest a sediment gravity flow or basal debris flow of a turbidite. Fossil assemblage of nerinia and coral (see Fig 3.18) is characteristic of the Upper Jurassic Zuloaga carbonate platform strata developing contemporaneously east of the Mezcalera Basin. Location of FHINS-T at NAD 27 Mexico Zone 13, 229,153E, 2,995,364N.

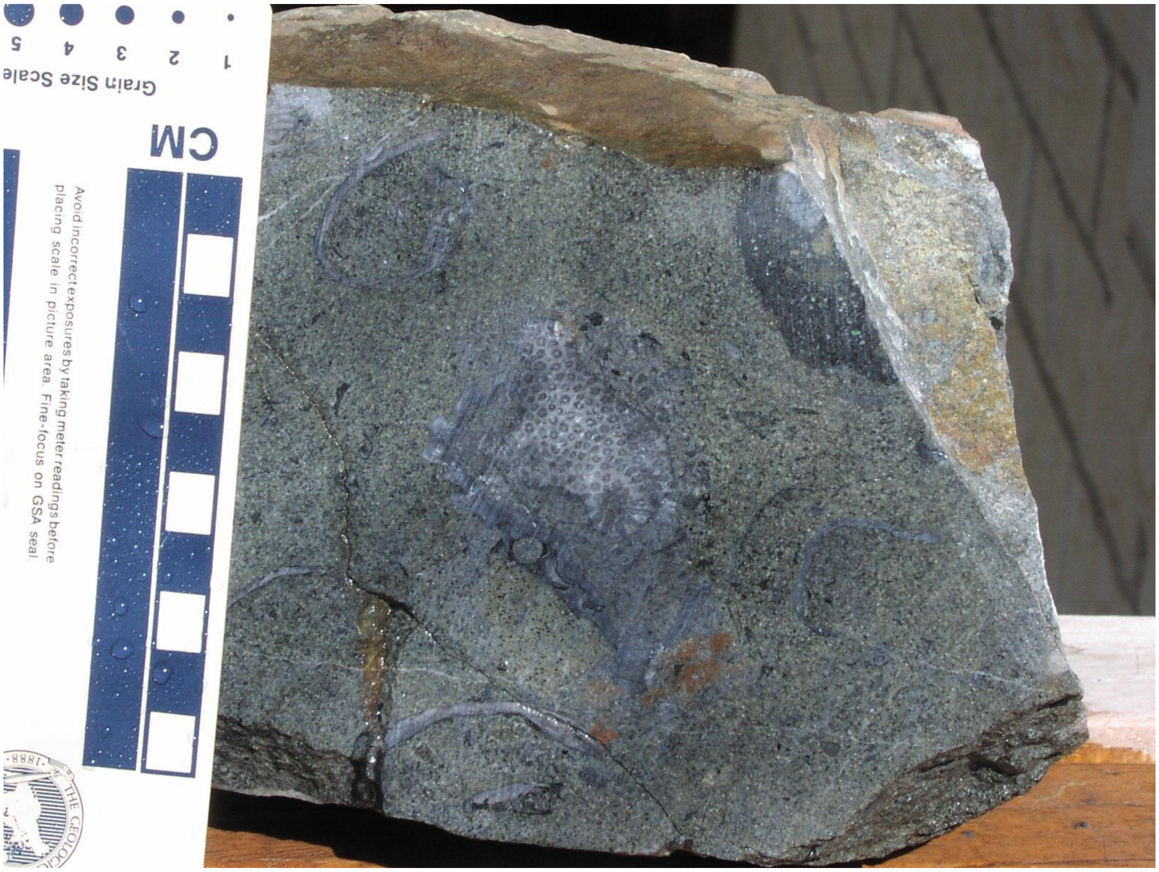


Figure 3.18 Coral and bivalves from the same sandy basal debris flow to a possible turbidite bed as Figure 3.17. Equi-dimensional fragments not oriented.

Figure 3.19 West-oriented belemnites (west is to the right, looking south) from the basal debris flow of the turbidite bed mapped at fossil locality BIN-T.

Photo taken on southeast side of arroyo at NAD 27 Mexico Zone 13, 229,236E, 2,994,793N.

Figure 3.20 In place ammonite at locality AINS-F3-17 on west side of fossil locality map.

Photo shows a mold of a segment of an ammonite whorl approximately 10 cm in diameter. Photo taken at NAD 27 Mexico Zone 13, 227,392E, 2,994,142N.

Figure 3.21 Collection of ammonite fragments from fossil bed south of fossil locality AF-F3-18.

Most ammonite fragments from AF-F3-18 (NAD 27 Mexico Zone 13, 229,113E, 2,994,497N appear to be from the same poorly exposed turbidite bed AF-AINS. The ammonites are suggestive of identified ammonites from Cucurpe (Timothy Lawton personal communication) One attempt to get them identified in Austin was unsuccessful and second attempt is being investigated in Mexico.

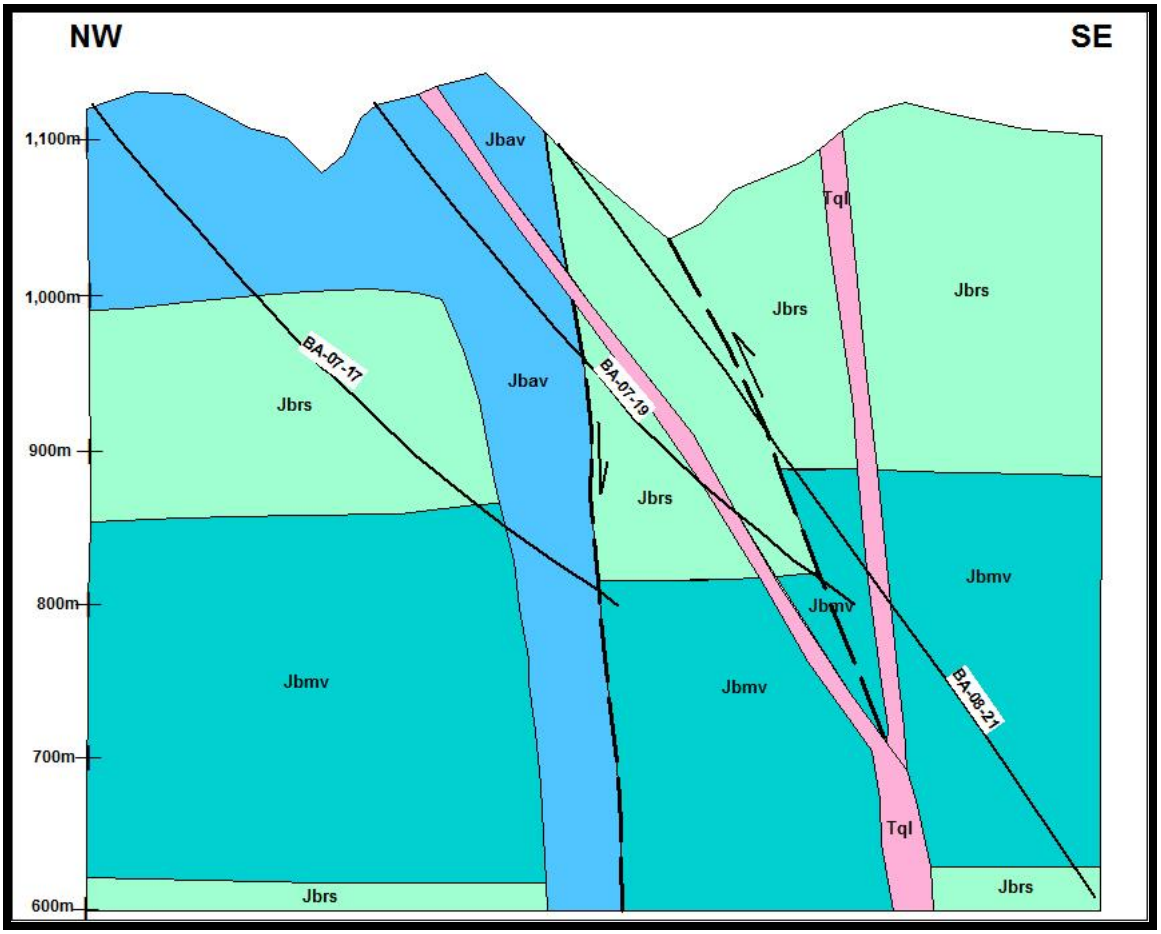


Figure 3.22 Drilling constrained Animas-Batopilas area cross section.

Cross-section illustrates relationships between various members of the Batopilas Formation as determined from exploration drilling on the east end of Animas Ridge (Fig. 3.15). Animas Ridge is the topographic ridge on the north side of the district. Drill hole BA-08-21 is the only documented locality reaching the Roncesvalles Member beneath the Minas Member. See Figure 3.12 for Legend except Tql is a quartz latite porphyry..

Figure 3.23 Fine-scale bedding in volcanoclastic facies of the Roncesvalles Member of the Batopilas Formation

Located on east side of Animas Hill (NAD 27 Mexico, Zone 13, 228,871E, 2,994,483N). Hammer is 38 cm long.

Figure 3.24 Belemnite and igneous fragments, in the black shale of the Roncesvalles Member of the Batopilas Formation.

Core (6.5cm in diameter) from drill hole BA06-08 (NAD 27 Mexico, Zone 13, 228,095E, 2,994,051N) at 37.7m depth adjacent to Pastrana Mine. Fossils, igneous fragments, lapilli and ash in shale illustrate volcanism in a marine environment.

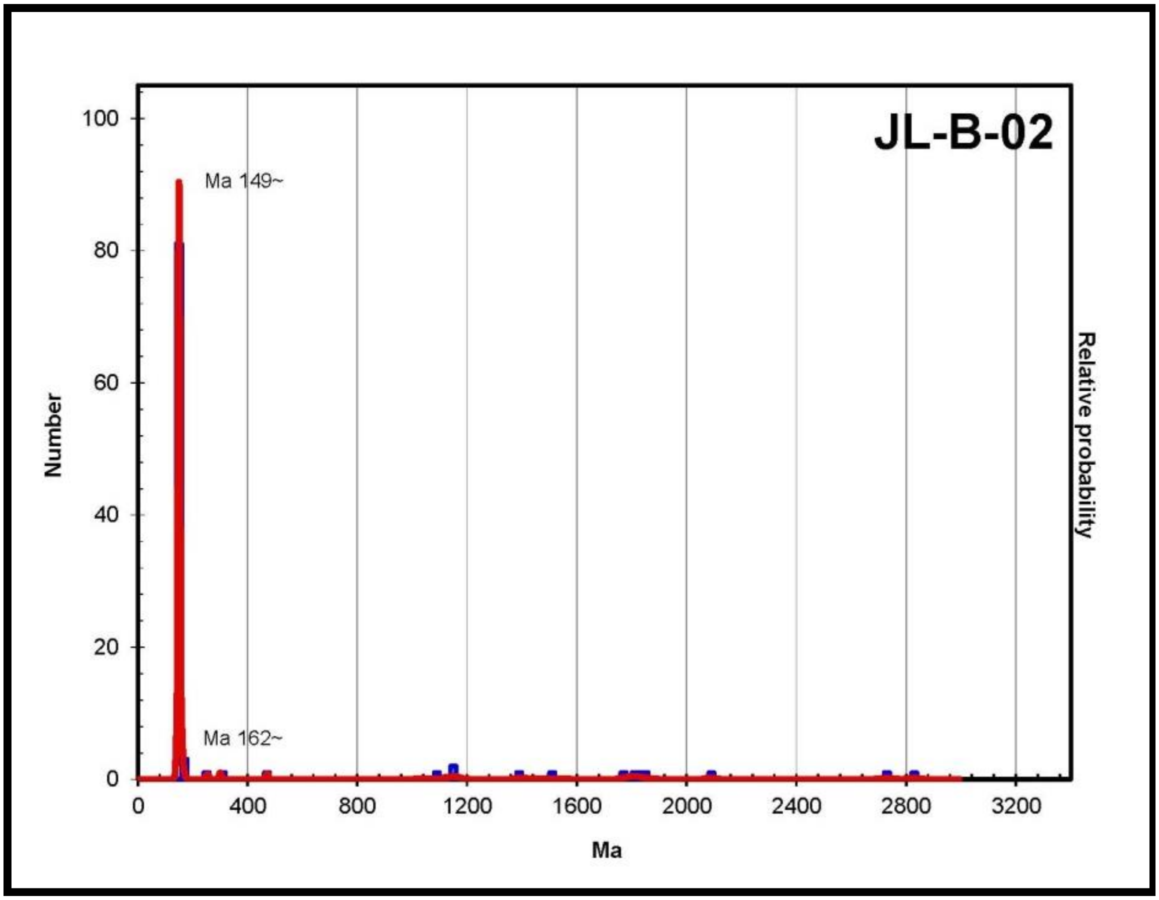


Figure 3.25 Relative Probability plot for the zircons from sample JLBL02

Zircons collected from the Roncesvalles Member of the Batopilas Formation near the Pastrana Mine between the Minas and Animas Members indicating an age of 149 Ma for the enclosed volcanic debris (See data in Appendix and Supplemental Data).

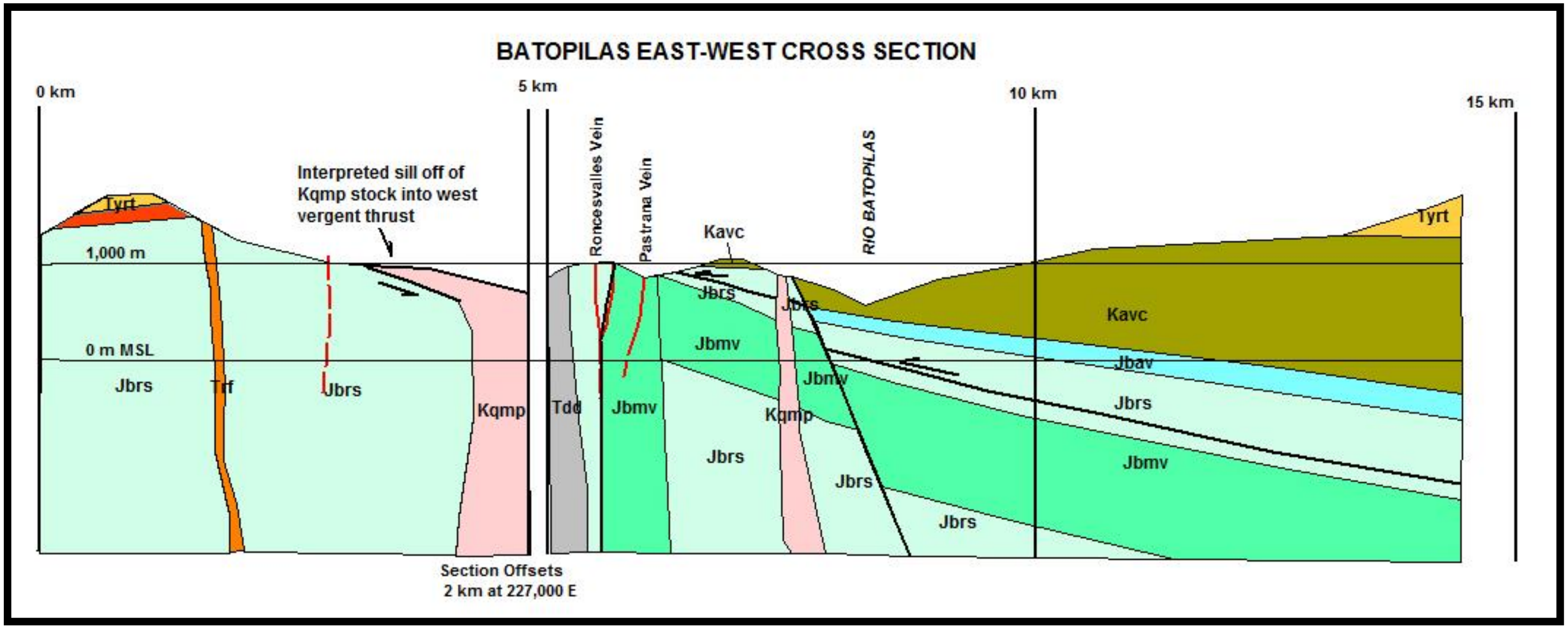


Figure 3.26 East-west cross section across Batopilas District as indicated on Fig.3.13.

Shows west-directed thrust faults and other important relationships (no vertical exaggeration). See Figure 3.12 for Explanation Figure 3.13 for section location. Sill interpreted off of Kqmp stock based on exploration drill results by Peñoles.

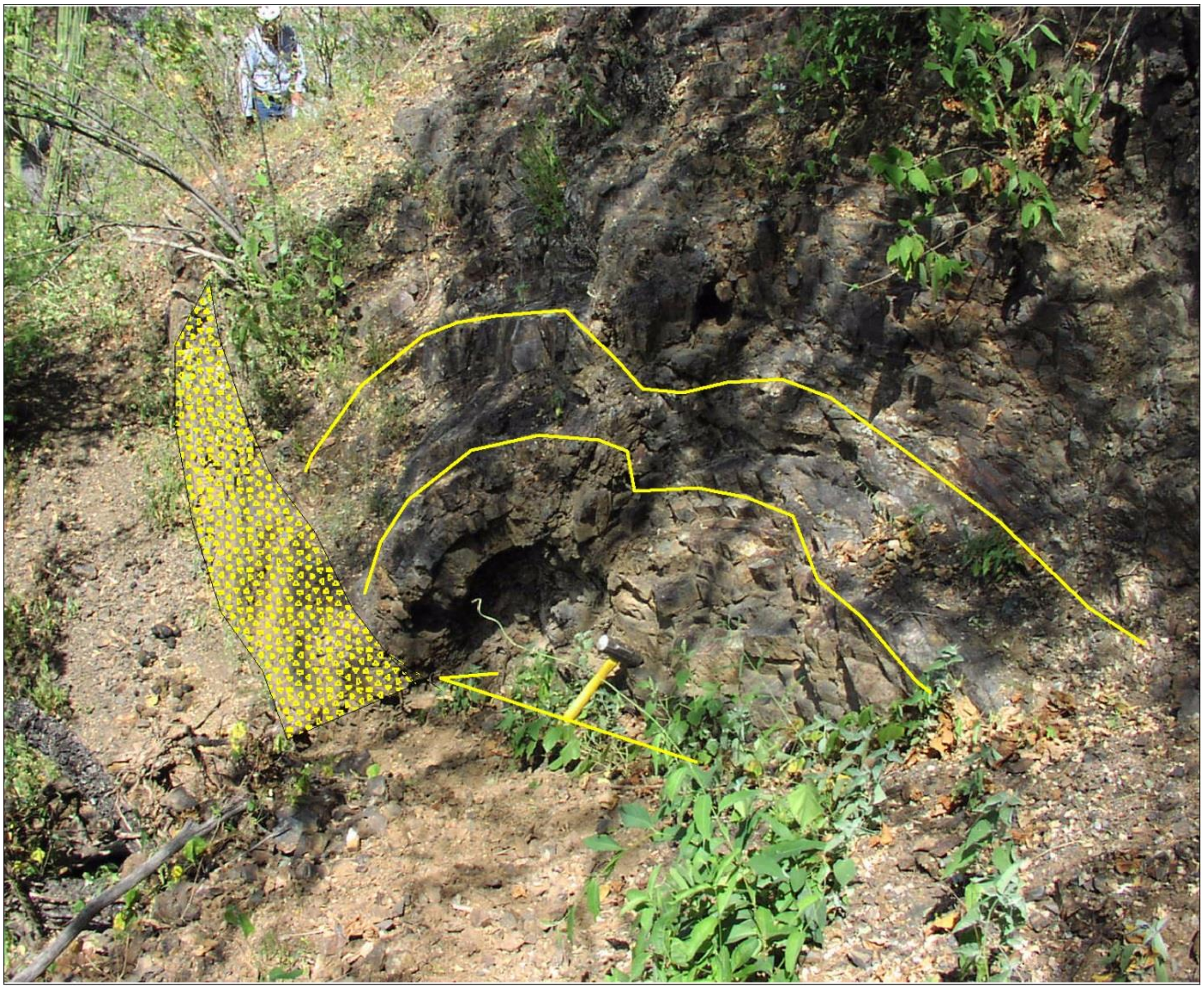
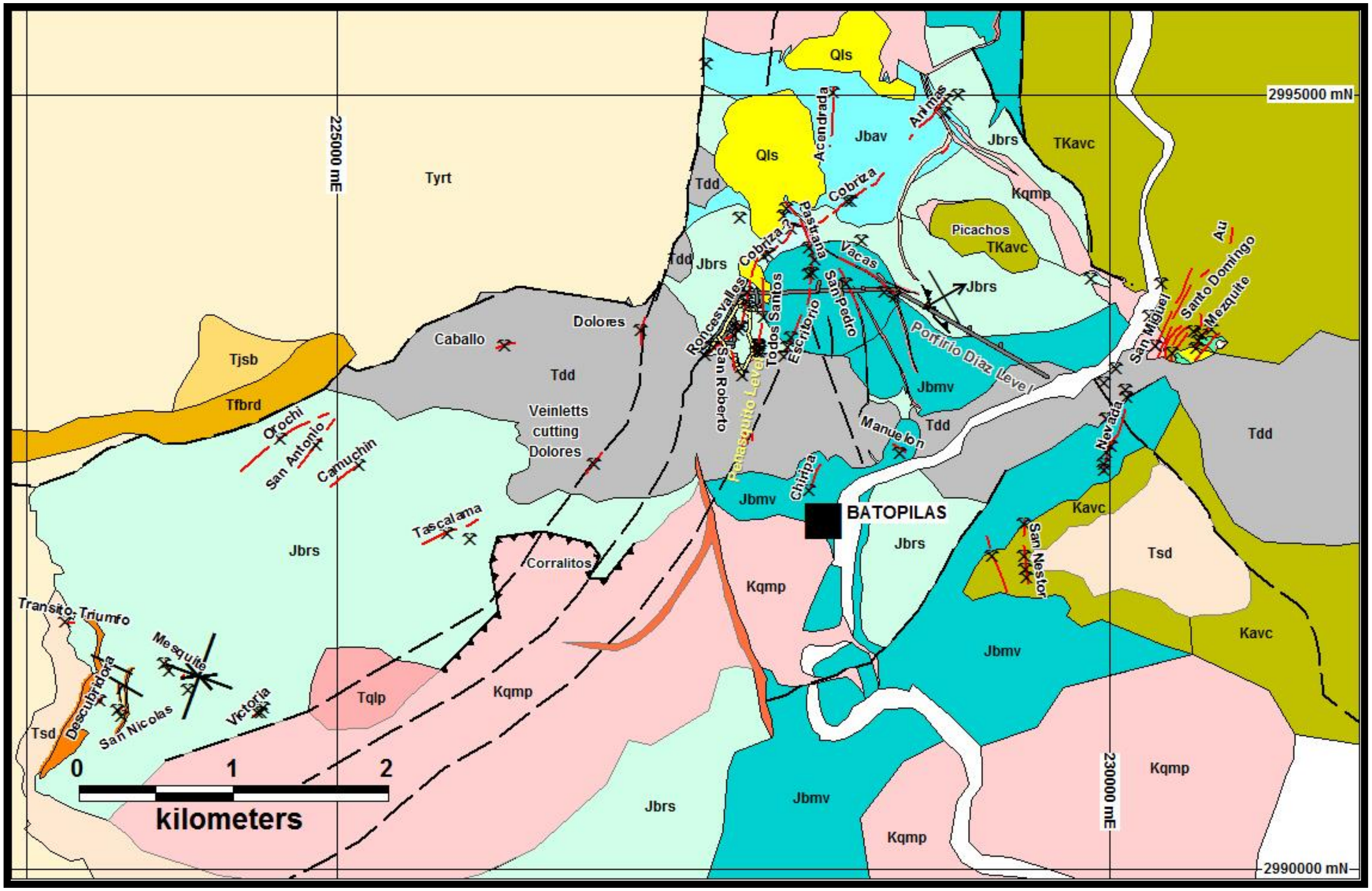


Figure 3.27 Photo of Fault-bend fold in Roncesvalles Member.

Located on northeast side of Minas flow dome (looking north, hammer 38 cm). Yellow lines follow bedding and patterned area is fault breccia. Photo taken looking north northwest at 228,908E 2,993,6000N UTM NAD27 Mexico Zone 13.

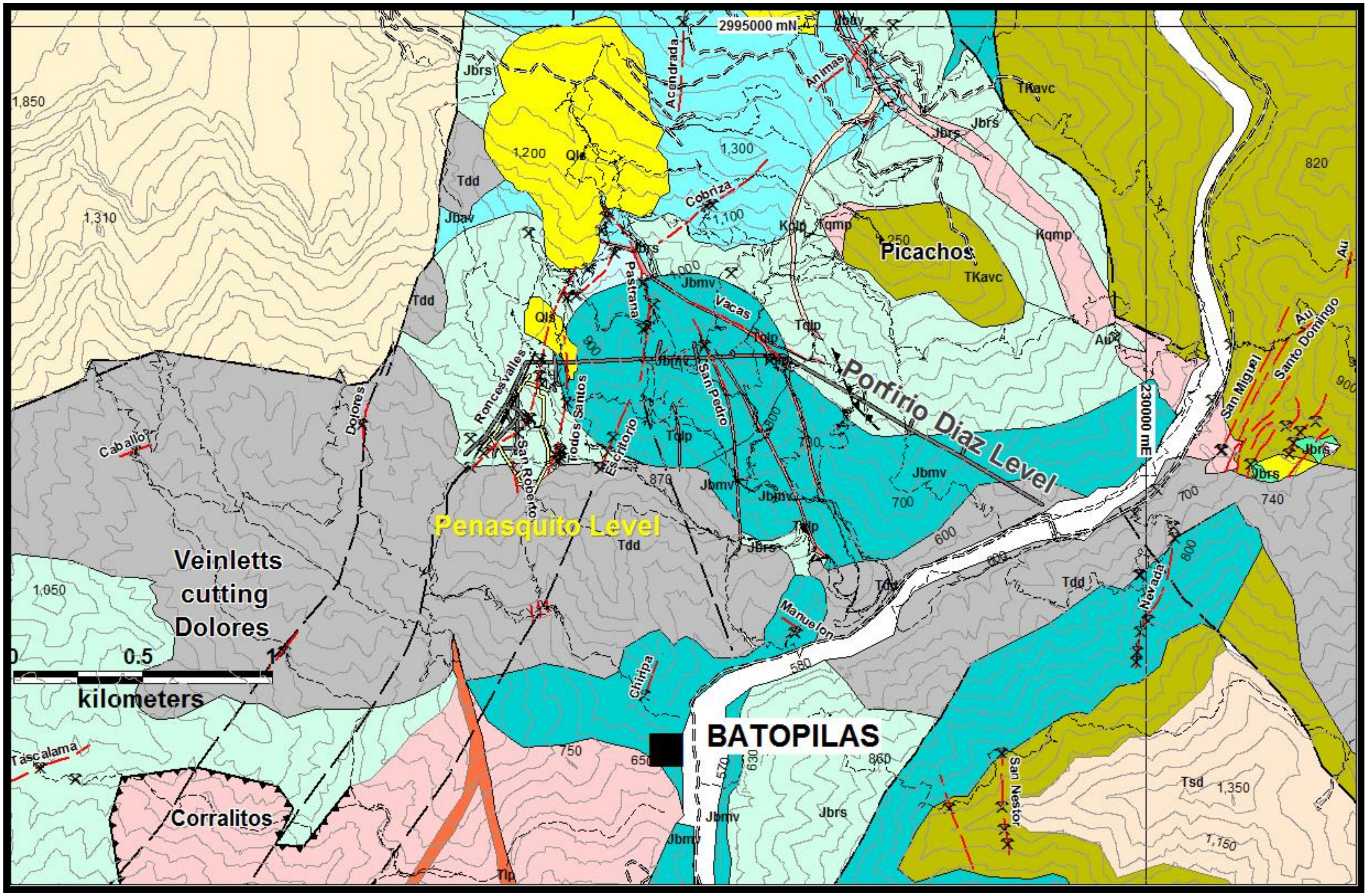


Qls
Acendrada
Animas
Jbav
Jbrs
TKavc
Tyrt
Tdd
Kqmp
Cobriza
Pastrana
Picachos
TKavc
Tdd
Jbrs
Cobriza
Vacas
San Pedro
Jbrs
Au
Santo Domingo
Mezquite
San Miguel
Dolores
Caballo
Roncesvalles
Todos Santos
Escritorio
Porfirio Diaz Level
Tjsb
Tfbrd
Tdd
San Roberto
Jbmv
Veinletts
cutting
Dolores
Orochi
San Antonio
Camuchin
Penasquito Level
Manuelon
Tdd
Nevada
Tdd
Chiripa
Jbmv
BATOPILAS
Kavc
Tascalama
Jbrs
Jbrs
San Nestor
Tsd
Corralitos
Kqmp
Transito-Triumfo
Mesquite
Jbmv
Kavc
Descubridora
San Nicolas
Victoria
Tqlp
Kqmp
Tsd
0
1
2
kilometers
Jbrs
Jbmv
Kqmp
Kqmp
225000 mE
230000 mE
2995000 mN
2990000 mN

Figure 3.28

Figure 3.28 Geologic map of the Batopilas silver district.

Highlights major veins, surface workings, and the Porfirio Diaz and Peñasquito drifts. UTM grid NAD 27 Zone 13, Mexico.



2995000 mN
Jbrs
Acendrada
Animas
Jbav
TKavc
Jbrs
1,850
1,200
Qls
1,300
820
Tdd
1,310
Cobriza
1,100
Jbav
Kqlp
Tqmp
Kqmp
Picachos
TKavc
Au
Pastrana
Jbmv
Vacas
Tdd
Qls
Tqlp
Au
Santo Domingo
San Miguel
Porfirio Diaz Level
Roncesvalles
Todos Santos
San Pedro
230000 mE
Dolores
Caballo
Escritorio
Tqlp
San Roberto
870
Jbmv
Jbrs
Jbrs
740
700
Penasquito Level
Tdd
600
Veinletts
cutting
Dolores
Tdd
1,050
Manuelon
Nevada
800
0
0.5
1
kilometers
580
Chiripa
BATOPILAS
Tascalama
750
650
570
630
860
San Nestor
Tsd
1,350
Corralitos
Jbmv
Jbrs
Jbmv
1,150
Tlp

Figure 3.29

Figure 3.29 Enlargement of the central part of the Batopilas District highlights Porfirio Diaz and Peñasquito drifts.

Figure 3.30 Quartz diorite mass appearing to have behaved plastically in the Roncesvalles Vein breccia body.

Breccia body observed on the Porfirio Diaz level of the Roncesvalles Vein. Fragments of breccia deformed the margins of the mass of igneous rock and protrude into it. Location NAD 27 Mexico, Zone 13, 227,486E, 2,993,502N.

Figure 3.31 Banded sulfide-calcite vein fragment in the Roncesvalles Vein breccia.

Breccia body contains fragments in which the coarse banding terminates against other rock masses in the breccia. Large light colored mass to the left is quartz diorite that displays textures indicative of being plastic when incorporated in the breccia. The vein fragment along with wall rock fragments are imbedded into the margin of the quartz diorite igneous mass. Located at Roncesvalles Vein Porfirio Diaz Level, NAD 27 Mexico, Zone 13, 227,492E, 2,993,511N.

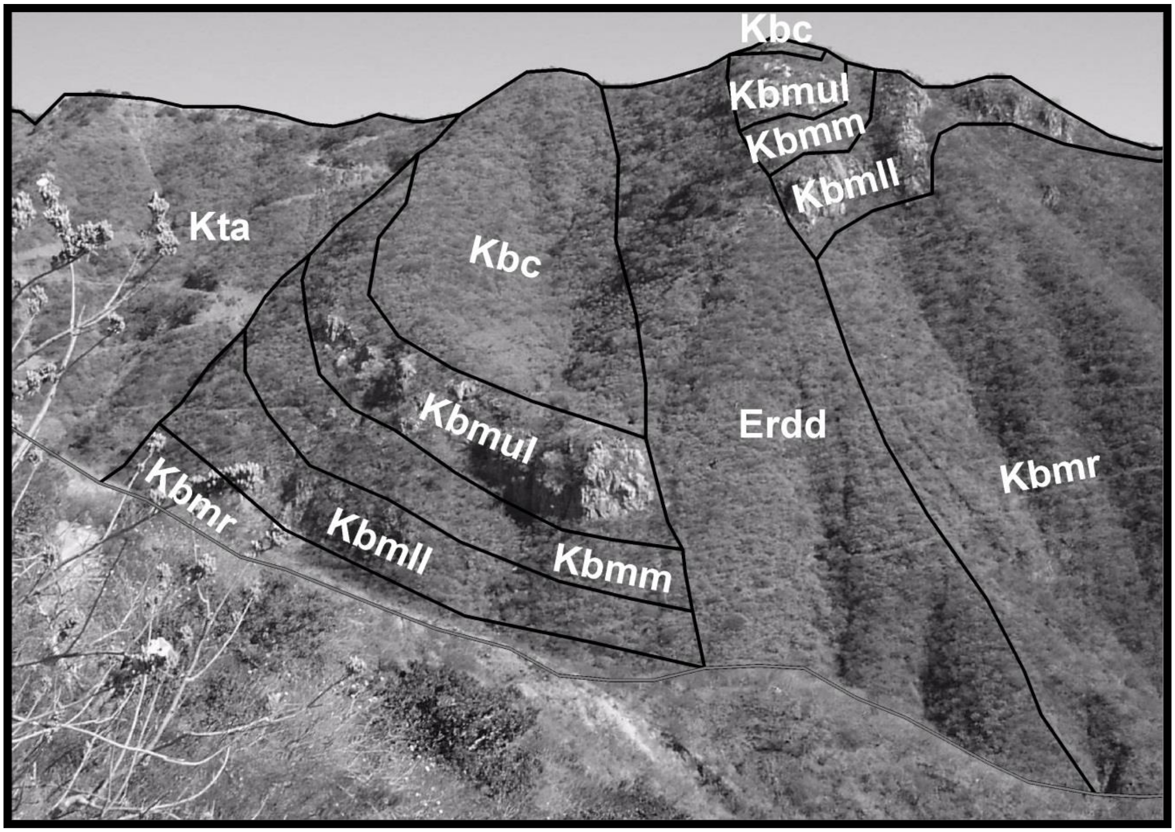


Figure 3.32 Overview of the synclinal fold at Lluvia del Oro.

The Bisbee Group formations are the Kbmr- Morita shales and sandstones, Kbmll- Mural Limestone, lower limestone, Kbmm- Mural Marl, Kbmul- Mural Upper Limestone and the Kbc- Cintura sandstones and shales. On top of a very irregular karsted surface Kta- Tarahumara Andesite is deposited. Some areas have a highly variable conglomerate between the Bisbee Group and the Tarahumara but it does not show in this view. The entire section is cut by Erdd- Eocene Rhyodacite Dike. Photo taken northeast from NAD 27 Mexico, Zone 13, 787,227E, 2,983,248N.

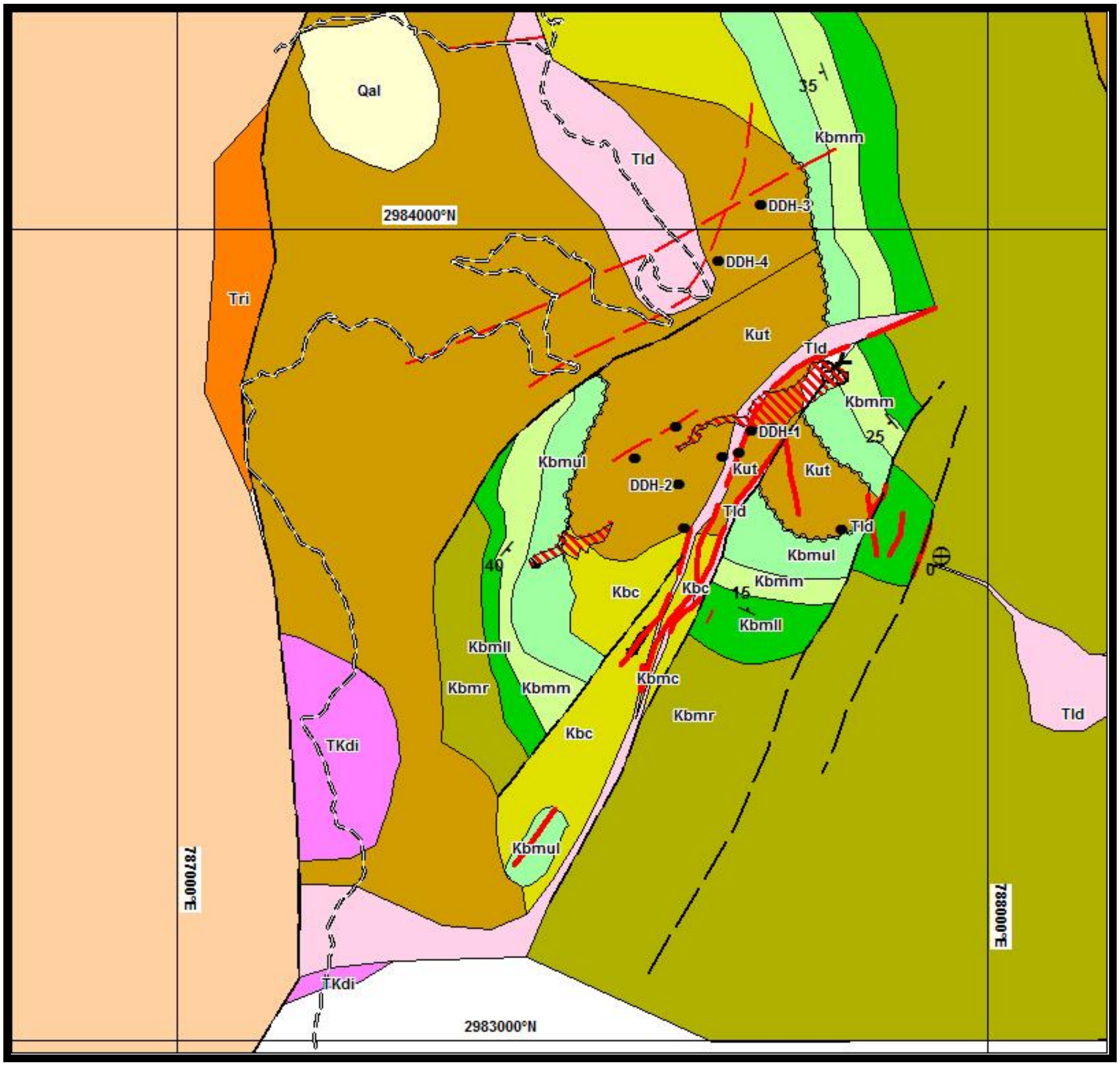


Figure 3.33 Revised map of the Lluvia del Oro Project area.

Units are the same as overview (Fig. 3.32) except for TKdi- a diorite intrusive and Tri- a Tertiary rhyolite dike. The red hachured area is the surface projection of mined out stopes. The wavy boundary on the map along the contact between the Upper Mural (Kbmul) and Tarahumara andesite (Kut) represents the karsted surface. Labeled drill holes from Consejo Recursos Minerales, 1988. Unlabeled drill holes from Peñoles located in field. One kilometer grid NAD 27 zone 12.

Figure 3.34 Photo of propylitic alteration of Middle Mural equivalent (Kbmm).

Photo taken looking south from 787,408E 2,983,603N UTM NAD27 Zone 12.

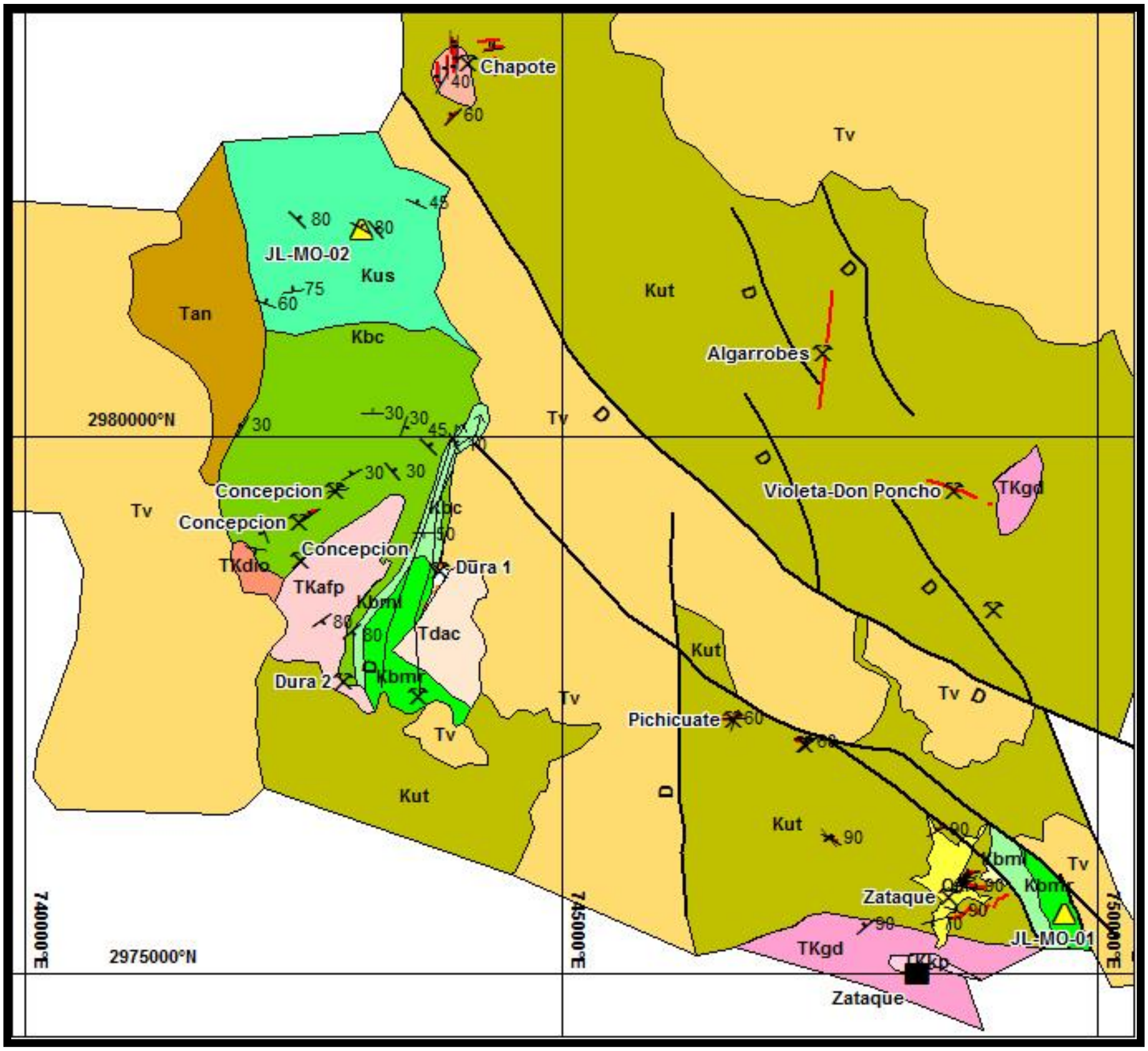


Figure 3.35 Geologic map of the Zataque map area.

Principal units are the Bisbee equivalent Morita (Kbmr) shale in the cores of anticlines the folded Mural Limestone (Kbml) capped by the Cintura (Kbc) shale and sandstone. A major northeast dipping unconformity lies on top of the Bisbee Group with significant thickness of sandstone and conglomerate (Kus). This accumulation of strata on the unconformity is probably quite variable based on mapping at Lluvia del Oro. On top of the unconformity derived strata lie volcanic strata correlated with the Upper Cretaceous Tarahumara, dominated with andesite flows, breccias and tuffs dipping approximately 15°northeast. The andesite strata are overlain by rhyolite welded tuffs (Tv) that are subhorizontal. The yellow triangles locate the two detrital zircon dating samples JL-MO-01 and JL-MO-02. Five kilometer grid is NAD 27 zone 12.

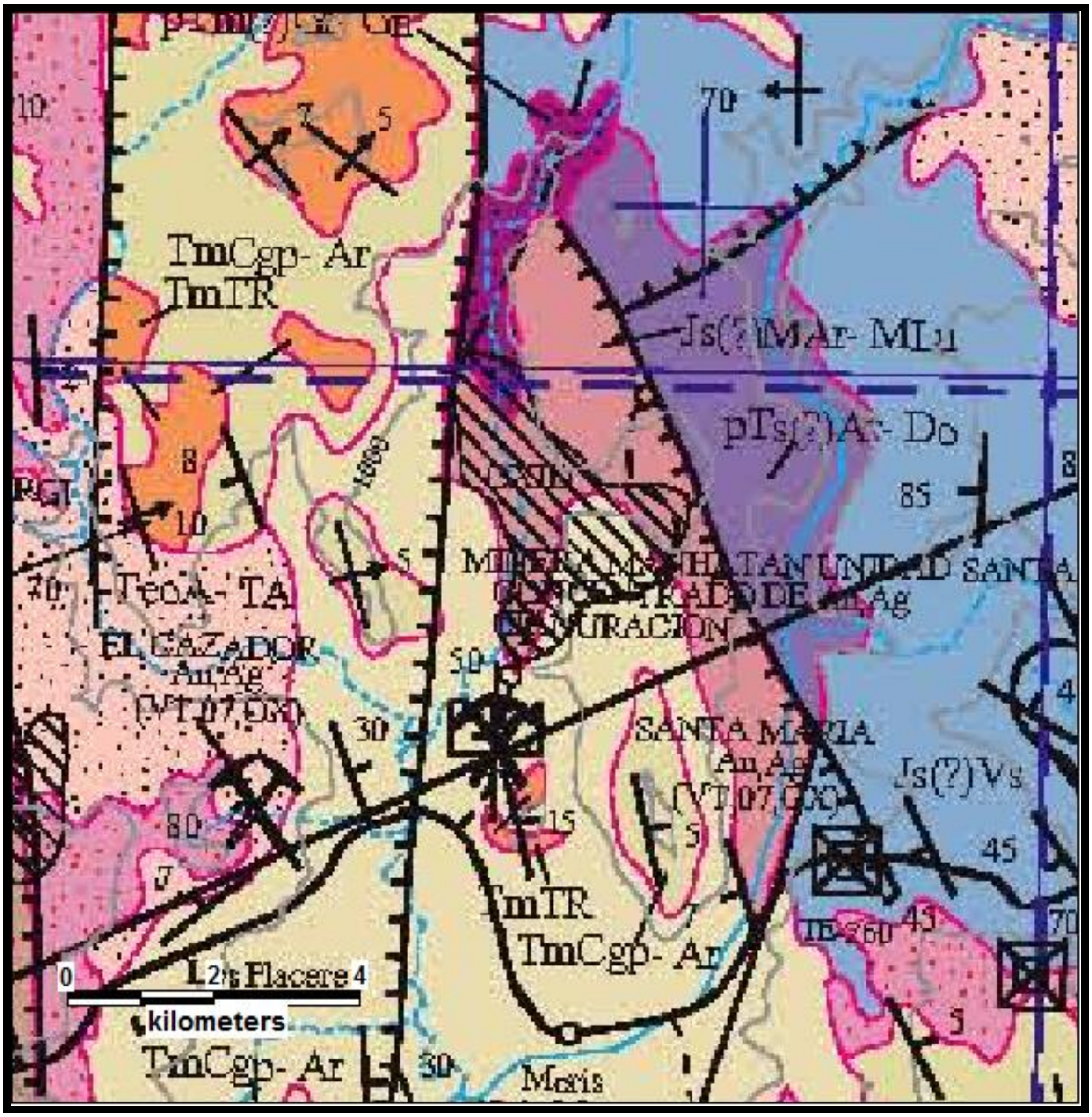


Figure 3.36 Published 1: 250,000 scale SGM map of the Moris, Chihuahua area.

The SGM 1:50,000 scale maps of the area are deemed less accurate by the author. They mapped the limestone as thrusted Cretaceous limestone of which there is no evidence. Figure 3.36 covers almost precisely the same area as Figure 3.37.

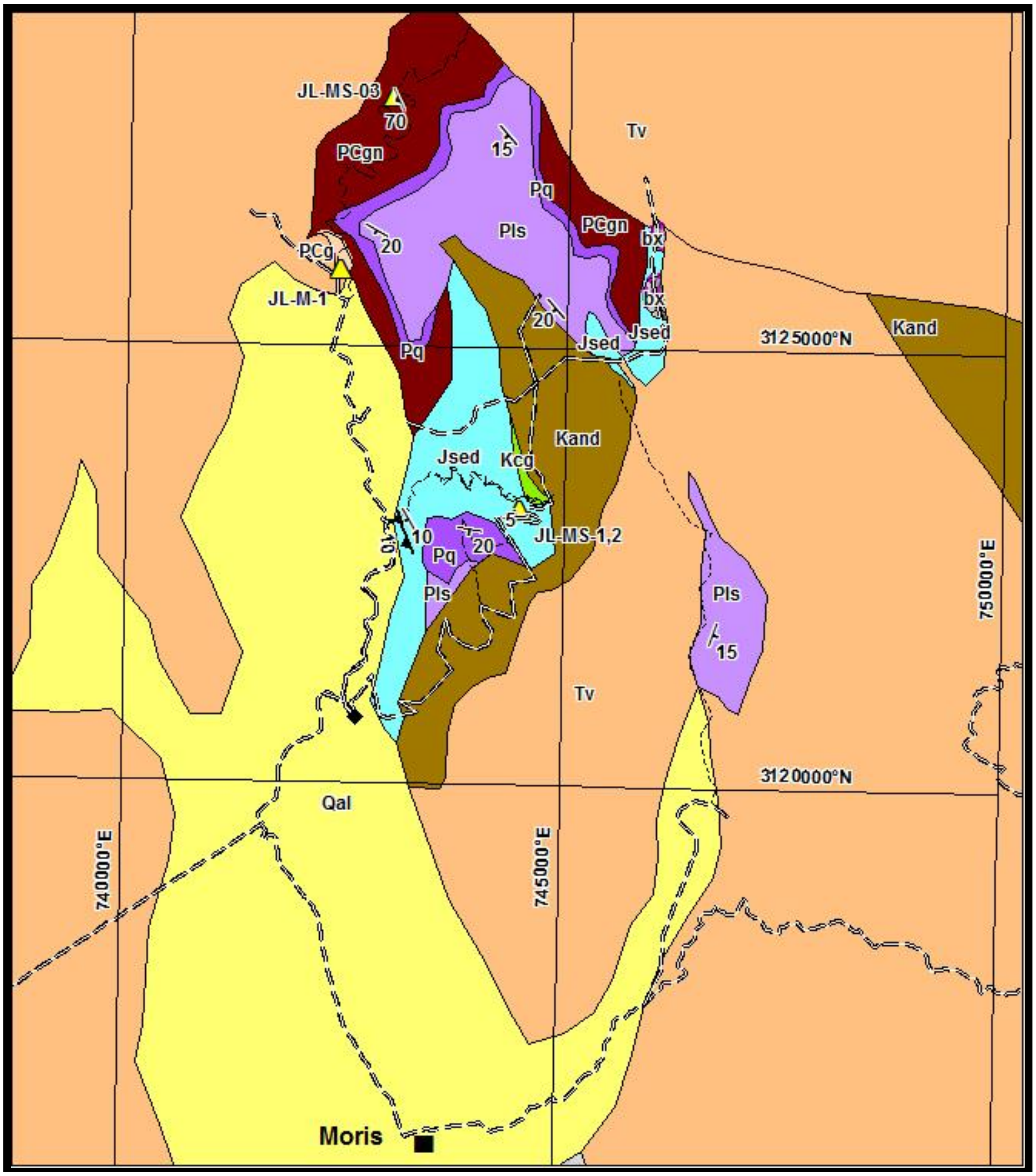


Figure 3.37 Geology of window to Jurassic and basement strata north of Moris, Chihuahua. Covers approximately same area as Fig. 3.36.

Precambrian gneiss (PCgn) is cut by a 1.44 Ga granite (PCg, see Appendix A, sample JL-M-1). The Paleozoic basal quartzite (Pq), rest on the gneiss and is overlain by Paleozoic limestone and dolomite (Pls). The Upper Jurassic marine shale (Jsed).overlaps the basement blocks. The breccia in northeast corner of window is a limestone landslide into the Jurassic shale. The surrounding units are various volcanic strata (Tv and Kan) and alluvium (Qal). The grid is 5 km UTM NAD27 zone12.

Figure 3.38 The U-Pb dated 1.44 Ga Precambrian granite (30 Zircons) collected from the northwest edge of the Pre-Jurassic basement at Moris, Chihuahua.

The 1.44 Ga U-Pb date (30 zircons) cut the surrounding gneiss that has yet to be dated. This sample is JLM-1 and is documented in Appendix A and the supplemental files.

Figure 3.39 East-directed thrust in the Jurassic shale north of Moris, Chihuahua.

It is located on the north side of the mouth of the canyon approximately 1 km north of Santa Maria at 743,082.5E, 3,123,017.3N (UTM Grid NAD27 Mexico Zone12). This canyon cuts the Jurassic strata between the two blocks of Precambrian through Paleozoic basement.

Figure 3.40 Conglomerate caps the Jurassic strata in the canyon 1 km north of Santa Maria.

This unit derived principally from shale and carbonate strata is similar to a conglomerate that caps the Jurassic at Arivechi, Sonora (Terán and others, 2005). Photo taken at 744,581E, 3,123,285N UTM NAD 27 Zone12.

Figure 3.41 Dated Moris Jurassic marine sandstone strata on flanks of Paleozoic basal quartzite.

All dated zircons were Archean and Proterozoic in age (see Appendix A), but both micro fossils and ammonites are upper Jurassic (Garcia Cortez and others, 2000; Herrera-Galvan and Cabañas- Villalba, 2004). The zircons are interpreted to have been derived from the adjacent quartzite and gneiss. Photo taken at 744,539E, 3,123,122N UTM NAD27 Mexico Zone 12. Hammer and handle are 28 cm long.

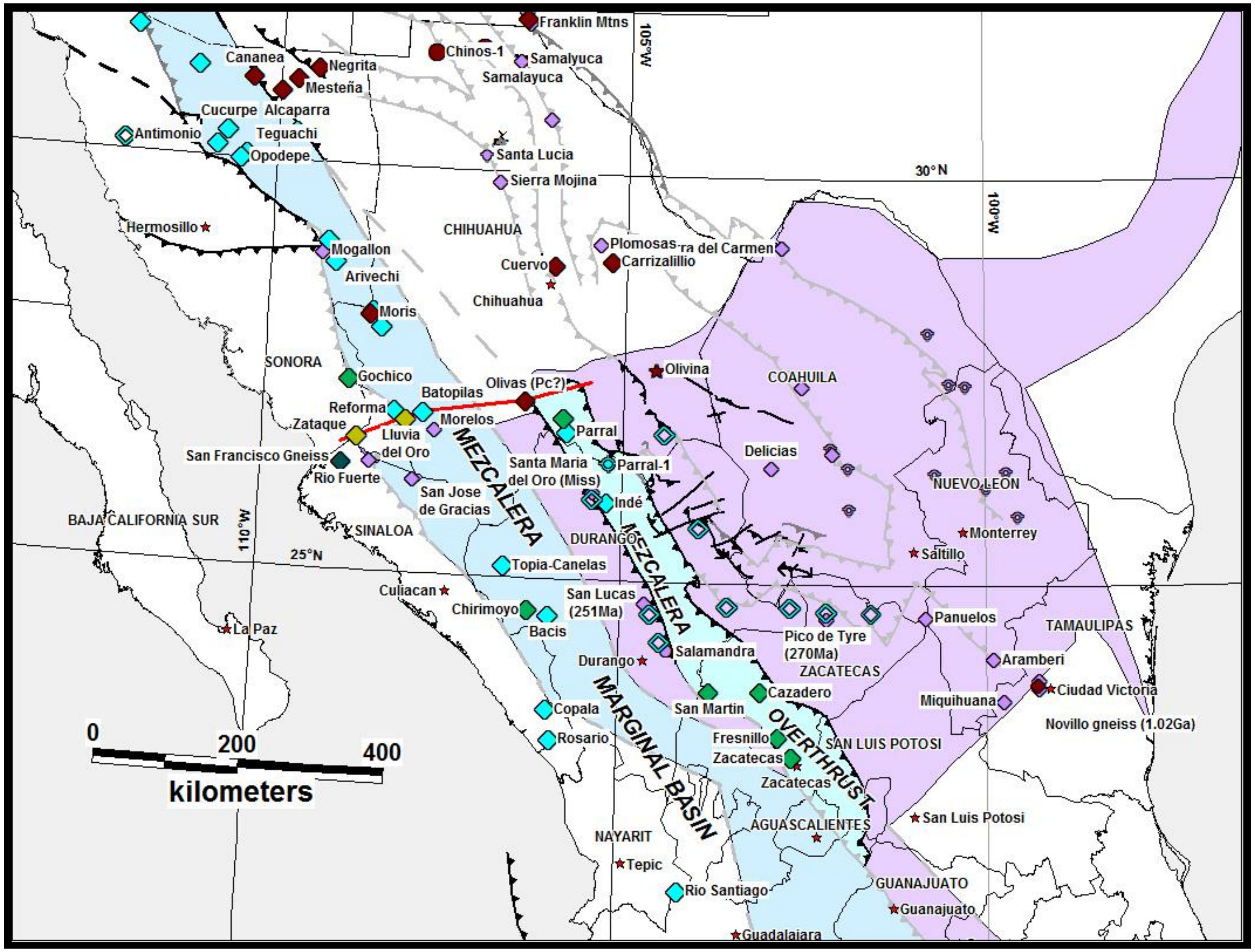


Figure 3.42 Basement map of northern Mexico locates the Batopilas Transect Z-M (red line) across the Mezcalera Basin and overthrust.

Z M

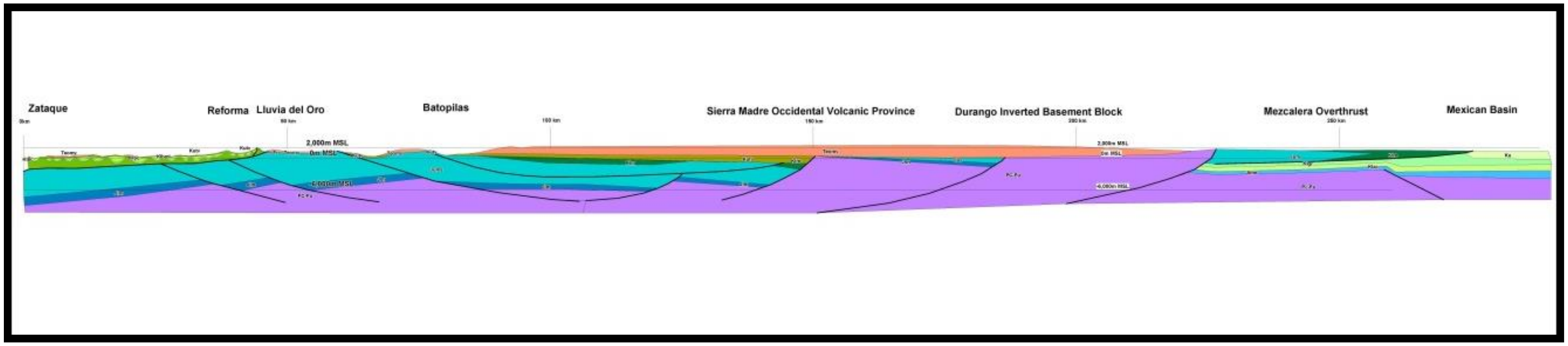


Figure 3.43 Batopilas transect Z-M is a 290 km regional cross-section through Batopilas across the Mezcalera Marginal Basin.

Section is generated from compilation of mapping at the projects presented in this chapter and other field observations made during the study. The section is projected from the far east edge of the Mezcalera Overthrust back to the west to the Zataque, Sinaloa area. The transect illustrates the overthrusting of the distal portion of the Bisbee Group on to the Marginal basin strata, internal thrusting within the basin strata adjusting for shortening, the thrusting on to the cratonic platform of the Mezcalera thrust that is then cut off from the source basin by the inverted basement block. The section has no vertical exaggeration so is presented in two halves Fig. 3.44 and Fig. 3.45 to make it more legible.

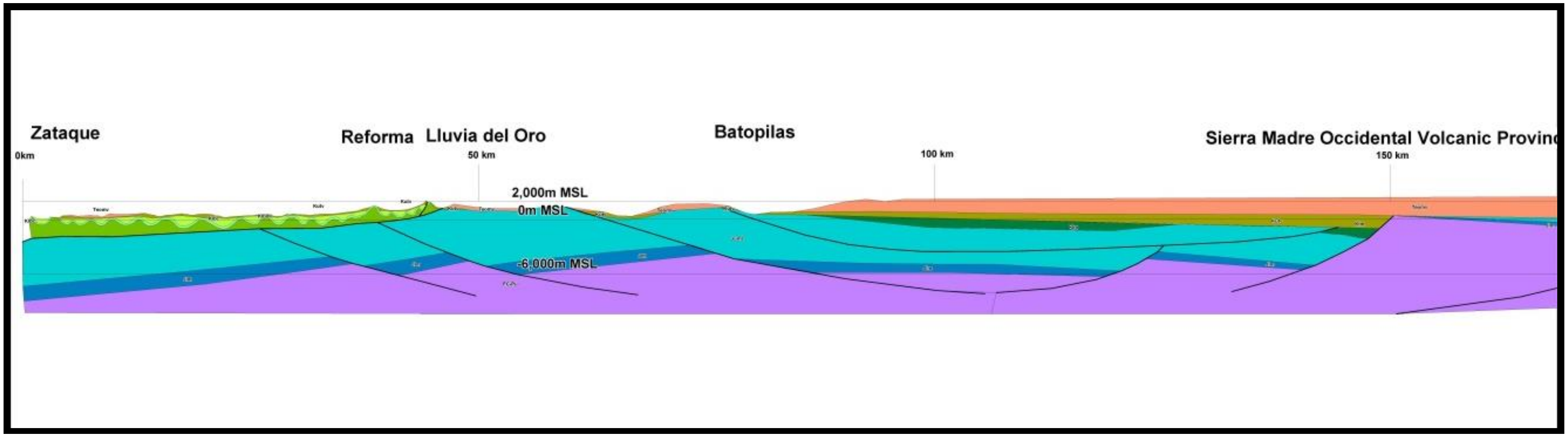


Figure 3.44 Regional cross section viewing the west half of the Batopilas transect.

Section to highlight the deformation within the Mezcalera Marginal basin and overthrusting of the basin by the offset distal part of the Bisbee delta.

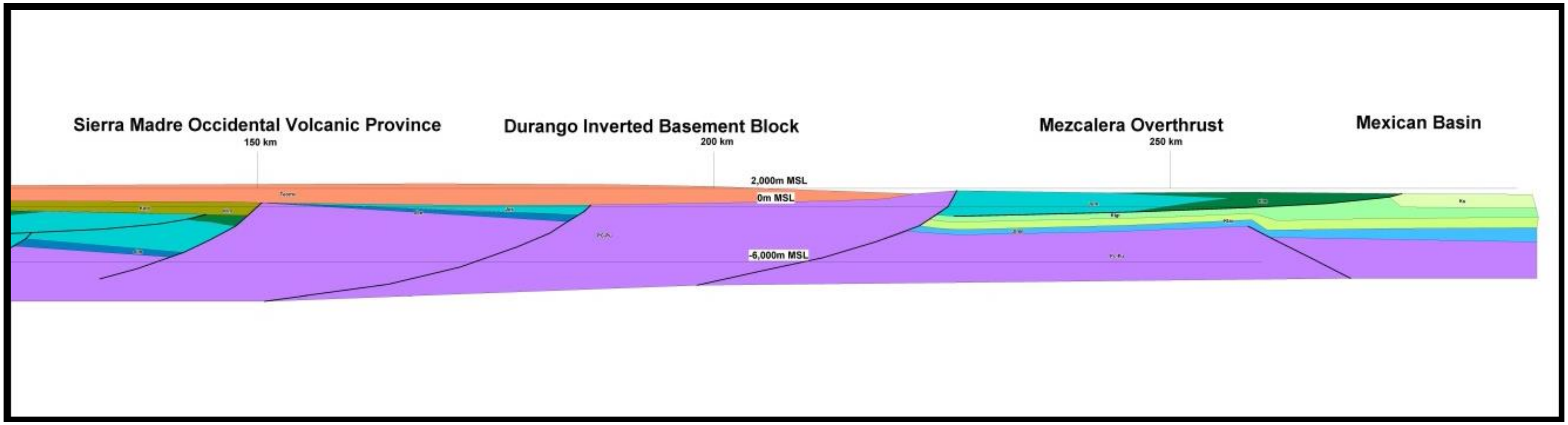


Figure 3.45 Regional cross section of the east half of the Batopilas transect.

Section highlights the inverted basement blocks along the eastern edge of the marginal basin and the klippe of the Mezcalera overthrust onto the central highlands platform.

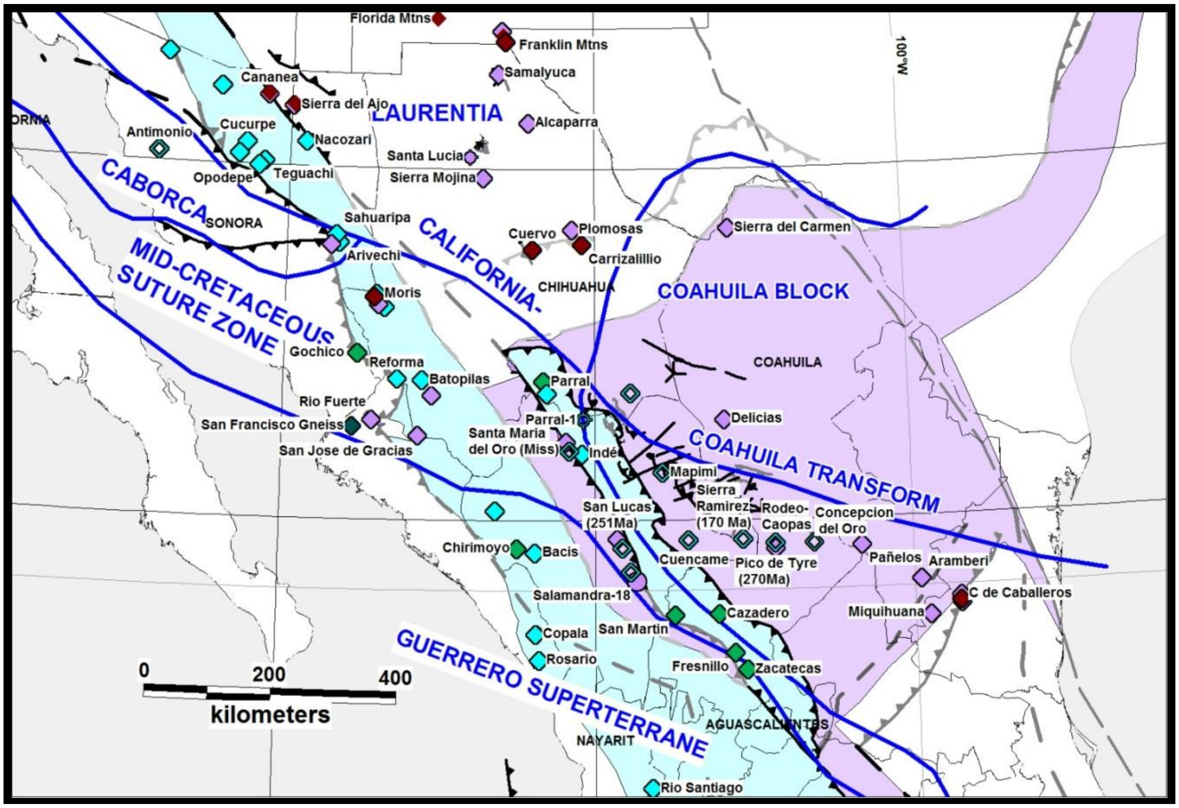


Figure 3.46 Terranes of northern Mexico as proposed by Dickinson and Lawton (2001) (dark blue lines trace their terrane boundaries). and the proposed distribution of Mid to Upper Jurassic deep water strata (light blue field).

Turbiditic and pelagic mud outcrops of Middle and Upper Jurassic slope and rise strata (light blue diamonds) define the proposed Mezcalera Basin and Overthrust (light blue). Open light blue diamonds are Nazas age outcrops on Paleozoic basement where documented and medium green are Lower Cretaceous deep shelf strata. Purple diamonds indicate interpreted and known Paleozoic basement and the tuscan red diamonds represent Precambrian basement outcrops. The dark green diamond at San Francisco gneiss indicates the isotopically determined Triassic age. Circles of the various colors represent drill hole intercepts of the color indicated unit. The light blue fields represent an interpretation of the basin containing these rise deposits as well as the same strata where they are thrust out-of-the-basin to the east in the Mezcalera Overthrust. The purple field represents the interpreted field of Ouachita age Paleozoic basement exposed in north central Mexico and in the Durango inverted basement block.

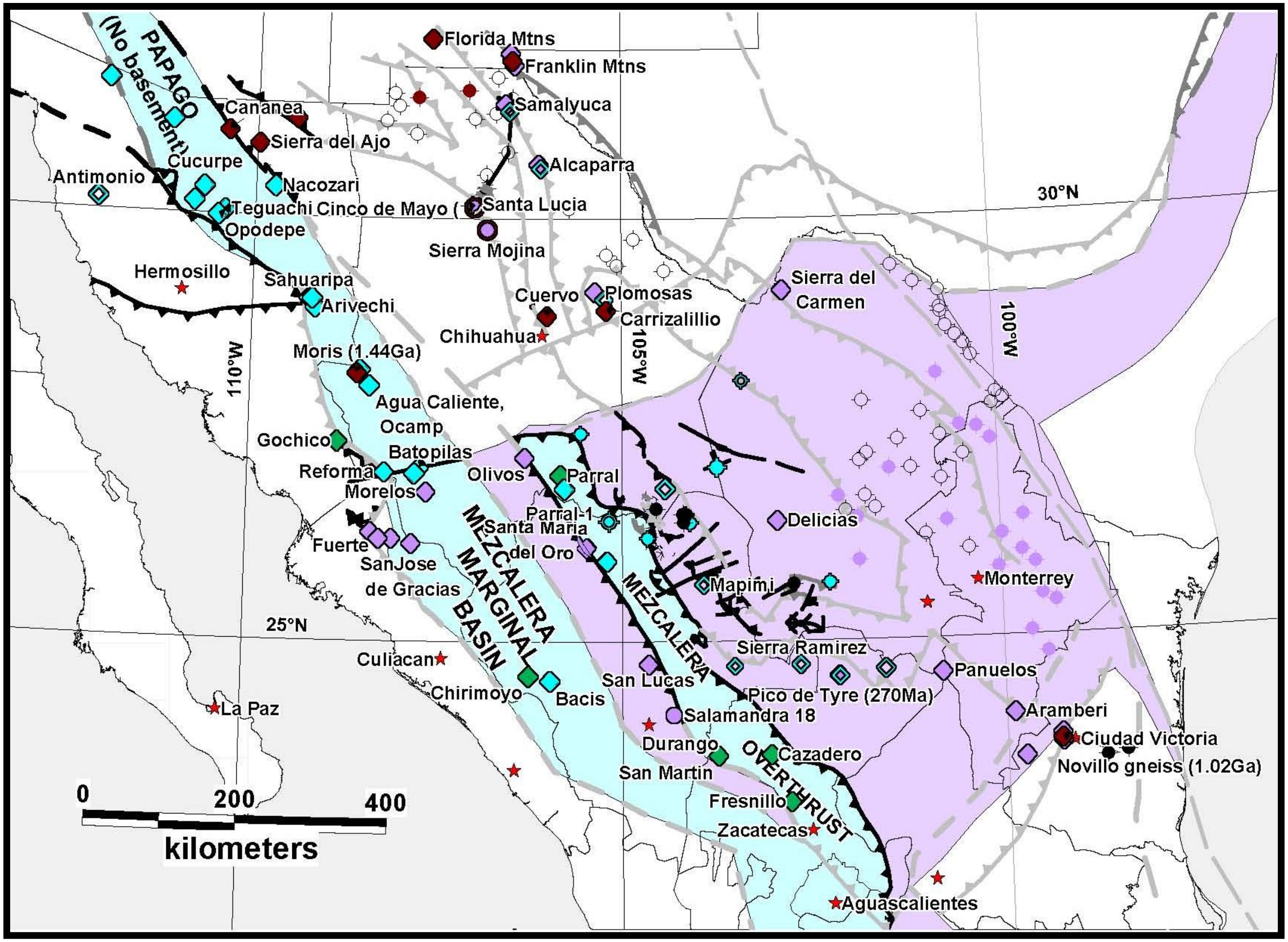

PAPAGO
(No basement)
Florida Mtns
Franklin Mtns
Samalyuca
Cananea
Sierra del Ajo
Alcaparra
Cucurpe
Antimonio
Nacozari
Teguachi
Cinco de Mayo
Santa Lucia
Opodepe
Sierra Mojina
30°N
Hermosillo
Sahuaripa
Arivechi
Cuervo
Plomosas
Carrizalillio
Chihuahua
Sierra del Carmen
110°W
105°W
100°W
Moris (1.44Ga)
Agua Caliente,
Ocamp
Gochico
Batopilas
Reforma
Olivos
Parral
Morelos
Parral-1
Santa Maria
del Oro
Delicias
Fuerte
SanJose
de Gracias
MEZCALERA
MARGINAL
BASIN
MEZCALERA
OVERTHRUST
Mapimi
Monterrey
25°N
Sierra Ramirez
Culiacan
Panuelos
San Lucas
Chirimoyo
Bacis
Pico de Tyre (270Ma)
La Paz
Salamandra 18
Aramberi
Ciudad Victoria
Durango
Cazadero
Novillo gneiss (1.02Ga)
San Martin
0
200
400
kilometers
Fresnillo
Zacatecas
Aguascalientes

Figure 3.47

Figure 3.47 Mezcalera Marginal Basin and overthrust belt separated by the Durango inverted basement block as proposed here. Symbols are as indicated in Figure 3.46

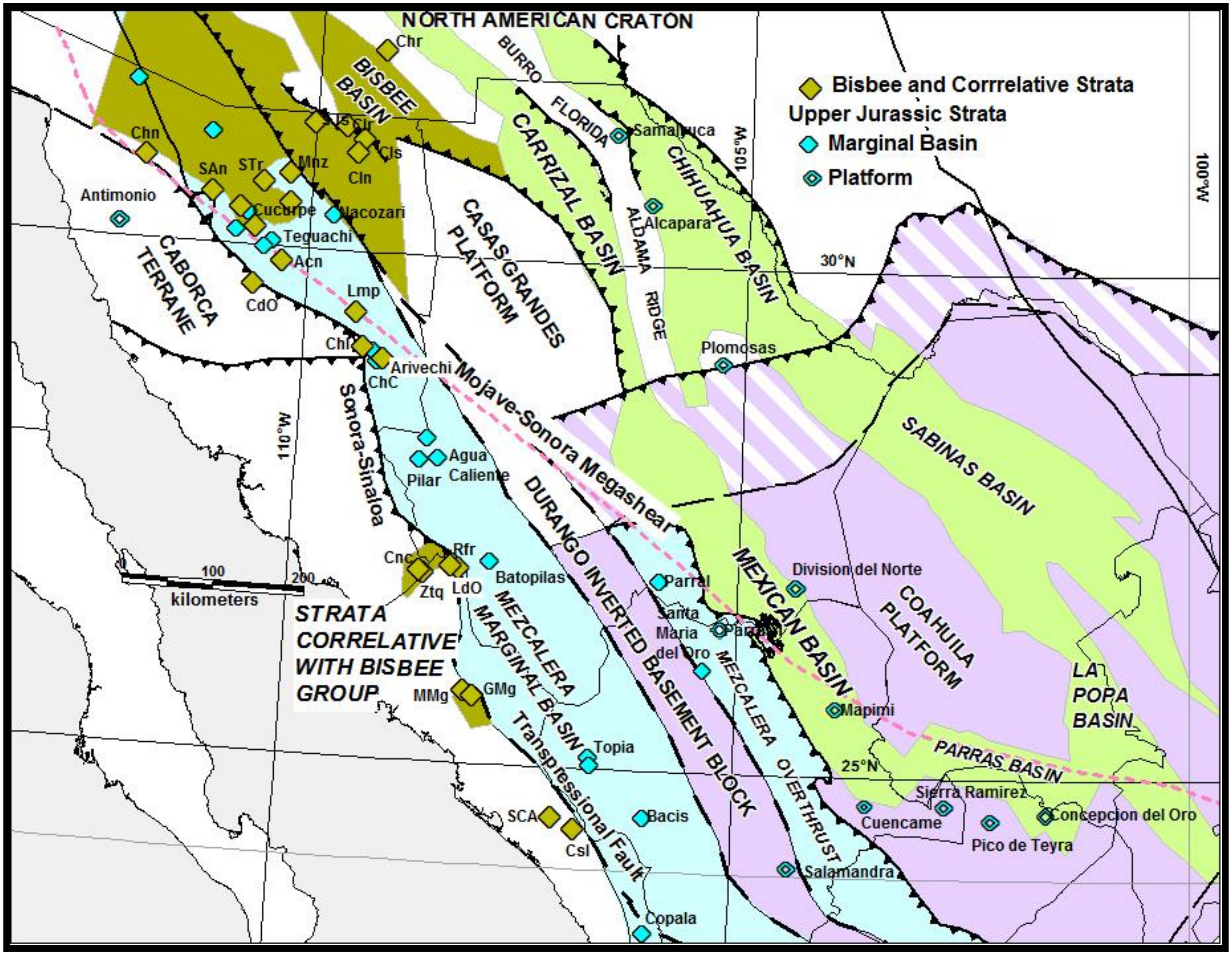

NORTH AMERICAN CRATON
Bisbee and Corrrelative Strata
Upper Jurassic Strata
Marginal Basin
Platform
BISBEE BASIN
BURRO FLORIDA
CARRIZAL BASIN
ALDAMA RIDGE
CHIHUAHUA BASIN
CASAS GRANDES PLATFORM
CABORCA TERRANE
Mojave-Sonora Megashear
Sonora-Sinaloa
DURANGO INVERTED BASEMENT BLOCK
MEZCALERA MARGINAL BASIN
Transpressional Fault
MEZCALERA OVERTHRUST
MEXICAN BASIN
SABINAS BASIN
COAHUILA PLATFORM
LA POPA BASIN
PARRAS BASIN
STRATA CORRELATIVE WITH BISBEE GROUP
105°W
100°W
110°W
30°N
25°N
100
200
kilometers
Chr
Chn
SAn
STr
Mnz
Cln
Cls
Clr
Antimonio
Cucurpe
Nacozari
Teguachi
Acn
CdO
Lmp
Chl
Arivechi
ChC
Agua Caliente
Pilar
Cnc
Rfr
Ztq
LdO
Batopilas
MMg
GMg
Topia
SCA
Csl
Bacis
Copala
Samalayuca
Alcapara
Plomosas
Parral
Santa Maria del Oro
Division del Norte
Mapimi
Cuencame
Sierra Ramirez
Concepcion del Oro
Pico de Teyra
Salamandra

Figure 3.48

Figure 3.48 A possible alternative to the Mojave-Sonora Megashear consistent with data in Sonora is a coast parallel fault proposed as the Sonora-Sinaloa transpressional fault.

Mural limestone found at Chn, Chanate; SAn, Santa Ana; Ccr, Cucurpe; Acn, Aconche; CdO, Cerro de Oro; ChC, Concha; Chl, Chiltepin; Cln, Culantrillo; Chr, Chiricahuas; Mnz, Manzanal. Lampasos, Lmp contains platform carbonates of equivalent age. Newly interpreted outcrops include LdO, Lluvia del Oro; Rfr, Reforma; Ztq, Zataque; Csl, Cosala; and GMg, Gallo at Magistral appear to also contain equivalent strata offset along this proposed transpressional fault.

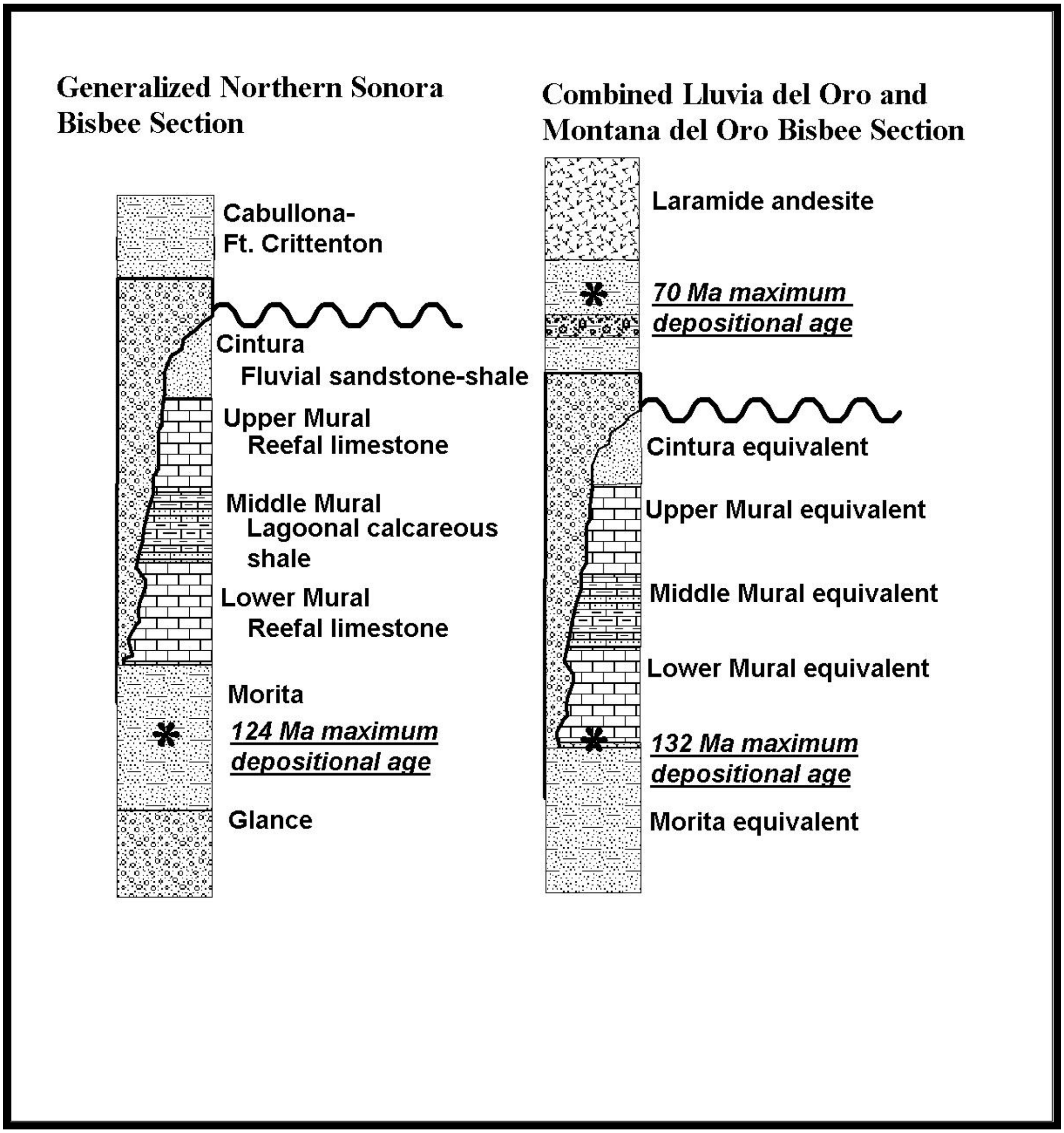


Figure 3.49 Lithologic sections of northeastern Sonora and the Sonora-Sinaloa-Chihuahua border region show the striking similarities between the two.

Mural sections in northern Sonora range from 100 to 500m (Jacques-Ayala 1995; Rosales-Dominguez and others., 1995). The Mural section at Lluvia del Oro is 100m and at Zataque approximately 300m. Ages are from samples JLMO-01 and JLMO-02 at Montaña del Oro and samples JLMS-01 and JLMS-02 at Arispe, Sonora.

CHAPTER 4: ORIGIN AND INVERSION OF MEXICO'S INTRACRATONIC CARRIZAL AND MEXICO BASINS: GEOLOGY AND MINERALIZATION

The current understanding of the intracratonic basins of northern Mexico has evolved from extensive stratigraphic studies beginning in the early 1900's often connected with petroleum exploration. The Carrizal Basin, a newly proposed basin in northern Mexico, has been defined by detailed and reconnaissance mapping and reanalysis of published data in the region surrounding the Cinco de Mayo Project (Sierra Santa Lucia) of MAG Silver Corporation, a Vancouver, British Columbia mining company (www.magsilver.com).

The following is a presentation of new mapping at Sierra Santa Lucia, Sierra Mojina 30 km southwest of Sierra Santa Lucia and Sierra Banco Lucero in north central Chihuahua area, supplemented by reconnaissance mapping from Samalayuca, 50 km south of El Paso, Texas to four small mining districts in the Chihuahua City area, Terrazas, Salemex and the Descubridora (within the Chihuahua City limits) (Figs. 4.1, 4.2). Detailed data collected in the Sierra Santa Lucia area (Cinco de Mayo Project) includes, in addition to the mapping, logging of 437 drill holes (208,000 m) of which 27 ranged from 900 to 1,200 m depth and only 11 of the total holes were chips from rotary drilling. A U-Pb date on detrital zircons from the basal Lower Cretaceous Las Vigas Formation encountered in a drill hole rounded out the data.

INTRODUCTION

The Cinco de Mayo Ag-Pb-Zn District is located in Sierra Santa Lucia in the Buenaventura Municipality, Chihuahua, Mexico. It is located 180km south southwest of the city of Juarez, Chihuahua situated across the Texas border from El Paso, Texas (Fig. 4.2). A new map of Sierra Santa Lucia based on mapping and logging of 437 exploration drill holes. New structural mapping between Sierra Samalayuca (50km south of Ciudad Juarez) and Sierra Santa Lucia integrated with published studies of the Chihuahua Basin (Berg, 1980) has led to a structural reinterpretation of the region.

Presented here is new and reinterpreted data that suggest that there is at least one additional extensional basin parallel to the Chihuahua Basin separated by a ridge of Paleozoic and older basement that includes the Cerro del Cuervo basement (Aldama Platform) in the Chihuahua City area and the Florida Mountain basement in southern New Mexico (Fig. 4.1). Another extensional basin appears to continue from the Bisbee Basin southeastward into the San Pedro de Corralitos area (Fig.4.1); volcanic cover prevents the conclusive determination if it is a parallel basin or a branch of the proposed Carrizal Basin, but a branch appears to fit the limited field observations best.

REGIONAL SETTING

Outcrops older than Lower Cretaceous are limited in northern Chihuahua, but some additional data are available from Pemex exploratory drilling. All of the localities mentioned in this discussion of Regional Setting are shown in Figure 4.5. The only documented outcrops of Precambrian in north-central Mexico are located at Sierra Cuervo (Los Filtros) 30 km north of Chihuahua City (Blount, 1983; Handschy and Dyer, 1987) and Carrizalillo 90 km east northeast of Chihuahua City (Blount, 1993), as reviewed in Poole and others (2005). Scattered occurrences of Paleozoic strata from the Pedregosa Basin are also found in far northwest Chihuahua from Nuevo Casas Grandes north to the American border (Palafox-R. and others, 1998; Garcia-Cortez. and others, 2003; Hernandez-Velazquez and others, 2003; Hernandez-Velazquez and others, 2002; Poole and others, 2005).

Pemex exploratory drilling bottomed in Precambrian basement in Chinos-1 and Moyotes-1 and in Paleozoic strata in Espia-1, Chinos-1, Centauro-1 and Ascencion-1 in a band along the Mexican border with New Mexico (Fig. 4.5). Ages of the basement intercepts referenced by Haenggi (2001) are a 1327±242 Ma (Rb-Sr) granite in the bottom of Pemex Los Chinos-1 and an 890±32 Ma (Rb-Sr) granite in the bottom of Pemex Moyotes-1.

Sierra Mojina (Fig. 4.5), 30 km to the south-southeast of Sierra Santa Lucia has had radiometric dates on selected clasts from the Las Vigas conglomerate near the base of the section on the east side of the range (Denison and others, 1970). Dating of these clasts indicated Neoproterozoic through Permo-Triassic clasts (Denison and others, 1970; Poole and others, 2005).

Monreal and Longoria (1999) point out that the Lower Cretaceous section at Alcaparra is greatly thinned compared to a typical Chihuahua Basin section suggesting the presence of a basement high. No age-constraining fossils were observed in the strata below the Benigno at Sierra Alcaparra by Rodriguez and Guerrero (1969). Visiting Sierra Alcaparra at the time of this study was considered inadvisable but Rodriguez and Guerrero's description of the Aleja Formation at the possible base of the section at Alcaparra is very similar to the regionally metamorphosed arkosic unit found at Sierra Santa Lucia and Sierra Mojina that are correlated with the Permian Scherrer Formation in this study. The pink skarn with epidote they describe probably represents the same piedmontite-rich propylitic alteration with clots of epidote after pedogenic caliche (calcite) as occurs at Sierras Santa Lucia and Mojina in originally arkosic mudstone strata.

The Villa Ahumada-1 exploration well of PEMEX cut 3,000 m of Lower Cretaceous and Upper Jurassic strata before cutting 2,000 m of Paleozoic strata of the

Pedregosa Basin (Wilson and others, 1969). The well is located along the line of section crossing the Carrizal Basin (Fig. 4.7). Wilson and others (1969) report 300 m of Wolfcampian within the 2,000 m of total Pedregosa Basin strata cut in the hole. If the Leonardian Scherrer Formation was cut, it would have to be above the reported Wolfcampian, but no further details of the stratigraphy of the hole are given.

A well-known outcrop of Permian strata in central Chihuahua is the Rara Formation at Sierra del Cuervo, 28km northeast of Chihuahua City, followed by Permian rocks at Plomosas, 88km northeast of Chihuahua City (Fig. 4.1, Handschy and Dyer, 1987). Within the Rara Formation an outcrop of Precambrian basement is mapped but its status as rooted basement or rafted block is uncertain (Handschy and Dyer, 1987). No thrusting or folding was observed (this study) in the Cretaceous of Sierra Peña Blanca (Sierra del Cuervo) as opposed to extensive east-directed thrusting at Rio Tinto (Terrazas) on Sierra Peña Blanca's west flank and west-directed thrusting along the east side of the range (Hennings, 1994). South of Aldama continuing to the Santa Eulalia Mineral District, Cretaceous strata are relatively flat-lying without significant folds or thrusts before disappearing beneath Tertiary volcanic rocks on the south side of the Santa Eulalia District.

A north-south zone that lacks significant deformation is bound both to the east and to the west by major shortening of basinal strata along with the outcrop of Permian basement north of Aldama; this suggests that the belt is underlain by a stable basement. This undeformed area is referred to as the Aldama Platform. Prior to this study the Aldama Platform was indicated as projecting northwest from the Chihuahua City area (Fig. 4.4) to the Mexican border of southeastern Arizona (Haenggi, 2002). With the definition of the Carrizal Basin by this study that separates the Aldama basement from that west of the Carrizal Basin, the basement of northwestern Chihuahua is proposed to be named the Casas Grandes Platform.

It is not known what basement lies to the west of Sierra Santa Lucia underlying the Casas Grandes Platform. New zircon ages from the exploration drill hole intercept of basal Cretaceous Las Vigas Formation at Sierra Santa Lucia (Cinco de Mayo) and new zircon ages on the basal Cretaceous conglomerate at Sierra Mojina (30 km south southeast of Sierra Santa Lucia), clast lithologies, and published dates on these clasts indicate that Mazatzal, Granite-Rhyolite Provinces and limited Grenville were probably exposed nearby in the Early Cretaceous. Lack of significant clast mixing in the conglomerate at Sierra Mojina also suggests a nearby source of the dominant Granite-Rhyolite Province clasts. Since a basin existed to the east of the platform in the Early Cretaceous, the zircons were probably being transported from the northwest to the southwest. Based on interpreted distributions of Grenville and Pan African basement (see Fig. 2.1), those zircons most likely were transported from the south. Permian Scherrer Formation may have also been exposed to the west and been the source of possible recycled zircons in the Las Vigas Formation.

CARRIZAL BASIN STRATIGRAPHY

The Carrizal Basin stratigraphy for the most part correlates well with that of the western Chihuahua Basin. The review of Chihuahua Basin stratigraphy by Monreal and Longoria (1999) discusses most stratigraphic nomenclature used in the region including ages and correlations. A diagrammatic lithostratigraphic cross section expanded from their original section of the Chihuahua Basin across the Carrizal Basin illustrates the similarities and the minor differences between the two basins (Fig. 4.6).

The only specific reference Monreal and Longoria (1999) made to a locality within the Carrizal Basin is that of Sierra Banco de Lucero (Fig. 4.7). The original mapping of Sierra Banco Lucero (Rodriguez-Torres and Guerrero, 1969) missed that a low angle fault cuts out a significant part of the section between the two main ridges of the range. As a result they did not recognize the section below the Loma Plata Limestone and gave it new local names Lucero Formation above the fault and Ahumado Formation below the fault. Monreal and Longoria (1999) correlated the Lucero with the Cuchillo chronostratigraphically and missed the fact that the limestone capping the Lucero (Rodriguez-Torres and Guerrero, 1969) was actually Benigno (this study). The missing Lagrima and Finlay above the Benigno actually crops out on the western part of the northeast ridge of Sierra Banco de Lucero but is faulted out on the more accessible east end of the range. This appears to have led to the previous stratigraphic misinterpretations (Fig. 4.6).

Precambrian outcrops are not known in the immediate study area but are known from Grenville age outcrops at Sierras del Cuervo and Carrizalillo to the southeast (Handschy and Dyer, 1987) and Mazatzal age outcrops in the Cananea, Sonora region to the northwest (Mesteña and Negrita, Fig. 4.5). Additional Precambrian ages come from Pemex exploration wells Chinos-1 and Moyotes-1 in northern Chihuahua (fig. 4.5).

The Upper Paleozoic stratigraphy, best known from Permian outcrops also at Sierras del Cuervo and Carrizalillo (Handschy and Dyer, 1987) and along the Chihuahua side of the New Mexico bootheel is not well understood because of limited outcrop. Some reasonable correlations can be made based on familiarity with Late Paleozoic Pedregosa Basin strata (Timothy Lawton, 2012, personal communication) studied in southeast Arizona (Blakely and Knepp, 1989).

Permian

Paleozoic strata of northern Chihuahua has limited exposures documented in the literature. The exposures include the Plomosas-Carrizalillo area between Chihuahua City and Ojinaga, Sierra del Cuervo northeast of Chihuahua City (Handschy and Dyer, 1987; Handschy and others, 1987) and the Pedregosa Basin strata that crop out between Nuevas Casas Grandes, Chihuahua and the bootheel of New Mexico (Fig. 4.2, Hernandez-Velasquez and others, 2002; 2003; Garcia-Cortz and others, 2000). Studies in southeastern Arizona (reviewed in Blakely and Knepp, 1989) produce the most detailed descriptions of what might be expected in the Pedregosa basin strata beneath the Mesozoic and Tertiary cover of north central Chihuahua.

Muddy arkosic red beds with pedogenic nodular caliche are interpreted as the Permian Scherrer Formation (Lawton, personal communication). Similar strata have been intersected in 7 exploration drill holes, in the Pozo Seco area of Sierra Santa Lucia (Fig. 4.7) that cut an inverted basement fault block defining the Casas Grandes Platform-Carrizal Basin margin. The first drill hole to cut these metamorphosed arkoses was an incomplete section of over 320 meters in ~20º dipping beds. In addition, this same unit has been mapped in outcrop near the base of the section on the east flank of Sierra Mojina 30km SSE of Cinco de Mayo (Fig. 4.8). The reddish groundmass contains significant piedmontite. Altered arkosic mudstone strata with similar lithology and alteration was described at the base of the section at Sierra Alcaparra (Rodriguez and Guerrero, 1969; Monreal and Longoria, 1999) and given the name Aleja Formation (Rodriguez and Guerrero, 1969). The non-fossiliferous Aleja was classified as Jurassic by Rodriguez and Guerrero (1969) because it was the oldest formation predating possible Navarrete and Las Vigas at Alcaparra.

The pervasive propylitic alteration dominated by piedmontite with localized clots of epidote-calcite-wollastonite in these red beds (Figs. 4.9, 4.10), appears to be regional in scope. It is identical in the two known localities of Pozo Seco core in the Sierra Santa Lucia and Sierra Mojina outcrops more than 30km apart and matches the description of the Aleja Formation 100km northeast at Sierra Alcaparra (Rodriguez and Guerrero, 1969). Similar alteration at three locations over 100 km apart suggests a regional thermal event as opposed to a local event proposed by Rodriguez and Guerrero (1969). The regional metamorphism does not appear to affect the unconformably overlying basal Cretaceous Las Vigas and Cuchillo Formations, suggesting some significant temporal break occurring between them and the regionally altered arkose. While the Las Vigas and Scherrer are very different lithologies some evidence of such a widespread thermal event would be expected to manifest itself in the overlying strata. K-Ar dating of a micaceous schist boulder (Denison and others, 1970) from the Las Vigas indicated a Permo-Triassic resetting of the metamorphic age with Grenville and Granite-Rhyolite Province zircons dominating the same rocks (this study). This suggests an extensive thermal event possibly is associated with the Permian magmatism indicated by Permian dated igneous clast at Sierra Mojina (Denison and others, 1970) and 2 Permo-Triassic zircons from this study.

In southeastern Arizona, similar mixed arkosic sandstone and carbonate lithologic units are described in the Permian Late Wolfcampian Earp to Lower Leonardian Scherrer Formations in the Pedregosa Basin (Blakely and Knepp, 1989). This red-bed facies reportedly (Blakely and Knepp, 1989) occurs on the platforms surrounding the Late Paleozoic Pedregosa Basin. The textural distribution of alteration appears to reflect the pedogenic caliche deposits observed in the Scherrer of Arizona (Lawton, personal communication). Possible Permian Scherrer Limestone crops out below the propylitically altered arkose at Mojina (Fig. 4.8). No fossils were observed at Mojina in the limestone similar to the southeast Arizona Scherrer Limestone (Blakely and Knepp, 1989) that reportedly lacked any fossils but echinoid spines.

The folded unreactive quartzite and conglomerate strata found in Sierra Samalayuca (Figs. 4.7, 4.11) have been generally accepted as Permian (Berg, 1980; Monreal and Longoria, 1999) but this has been disputed (Haenggi and Muehlberger, 2005) solely on the basis of overlying strata age interpretations. Whether they are Pre-Jurassic or Pre-Neocomian, they may still be Permian and based on the review of Blakely and Knepp (1989), with the most likely correlation being coarse conglomeritic quartzites of the Permian Scherrer Formation. These strata are thrust up through Upper Jurassic Casita Formation (Monreal and Longoria, 1999) along high angle reverse faults as an inverted basement block. Samalayuca strata reportedly lack any obvious metamorphism beyond tectonic shearing (Berg, 1980; Monreal and Longoria, 1999), but the author's observations of chlorite and epidote veining indicate some propylitic alteration occurs along with the tectonic shearing of the generally non-reactive rock.

The nearest documented Paleozoic strata are at the base of PEMEX exploration drill hole Villa Ahumada-1 that reportedly intersected 2,000m of Pedregosa Basin strata in the middle of the Mesozoic basin after starting in Lower Cretaceous. No depth was given, but most exploration holes in the region are typically drilled to 5,000m unless they intersect basement. This would imply 3,000m of Lower Cretaceous and Jurassic strata in the basin.

Many presumed Permian exposures (for example, Samalayuca and Sierra Mojina) and drill intercepts (for example Sierra Santa Lucia) are inverted basement blocks on the west sides of the tectonically shortened Chihuahua and Carrizal Basins. The Aleja at Sierra Alcaparra also appears structurally consistent with an inverted basement block again on the west side of the Chihuahua Basin. This will be further discussed under regional reconnaissance (Fig. 4.62)

Jurassic Strata

Outcrops of Jurassic strata have not been documented in the Carrizal Basin. The Upper Jurassic Casita formation is widely recognized in the Chihuahua Basin based on stratigraphy and paleontology (Monreal and Longoria, 1999) and is reported to occur in Pemex Banco Lucero-1 and Villa Ahumada-1 (unpublished PEMEX cross section and Haenggi, 2002). The only Jurassic strata cropping out in the map area is Casita Formation around the inverted basement block at Samalayuca (Fig. 4.7) along the west edge of the Chihuahua Basin (Monreal and Longoria, 1999). The Aleja Formation of Sierra Alcaparra is assumed to be Upper Jurassic based on stratigraphic position (Rodriguez and Guerrero, 1969) but based on regional lithologies, metamorphic character and stratigraphic position, it appears more likely to be Permian Scherrer Formation as discussed above.

Las Vigas (Klv)

The Las Vigas Formation at the base of the typical Cretaceous section is one of the more widespread units. Lack of significant fossil content makes its age known mostly by inference (Haenggi, 2001) as it lies on Paleozoic and Jurassic strata and underlies the Lower Cuchillo lagoonal facies in the study area. Haenggi compiled thickness data from both measured sections and PEMEX drill data to produce an isopach map of the Las Vigas Formation. Re-contouring Haenggi's (2001) data (Fig. 4.4) with several new data points and geologic input accentuates the structural ridge separating the Chihuahua Basin from the Carrizal Basin as defined in this study (Fig. 4.12). It should be noted that structural repetition and deletion to be discussed later may greatly affect thickness estimates in the deformed basins.

Las Vigas Formation crops out in Sierra Mojina (Fig. 4.8) and occurs in minor amounts in the 7 drill holes penetrating to the Permian at Pozo Seco in Sierra Santa Lucia (Fig. 4.7). The Las Vigas is not known to crop out in the Santa Lucia map area. The Sierra Mojina outcrops consist of mudstones, siltstones, poorly sorted coarse sandstones and conglomerates greenish-gray, orange-red to maroon (Fig. 4.13). The Las Vigas is easily distinguished from the underlying Scherrer sandstones principally from the lack of pervasive propylitic alteration found in the Scherrer. Some weak propylitic alteration was observed along fractures aligned along trend with the mineralization at Sierra Mojina but alteration was not apparent away from the strike of the veins. Clasts of schist and metamorphic quartz indicate a principally Precambrian basement source with minor subaerial volcanic and intrusive sources (Fig. 4.14, dated sample see Appendix A).

New U-Pb detrital zircon data was acquired on a bulk sample of the conglomerate for this study (see Figure 4.14 and Appendix A). The conglomerate clasts make up about 75% of the rock with a red silty sand forming the matrix. The clasts consist of 70% schist, 25% quartz mostly from white quartz veins that cut the schist and 2% limestone clasts. The previously dated igneous clasts (both intrusive and volcanic) make up an estimated 1% of the clasts and were not observed in the dated sample but did appear to contribute two Permo-Triassic zircons and three Cambro-Ordovician zircons. Most zircons appear to come from 1.1 Ga Grenville Province (13/100 zircons) and 1.3 to 1.55 Ga Granite Rhyolite Province (20 zircons) rocks. The Paleoproterozoic zircons (9/100) most likely represent recycled zircons possibly from the Permian Scherrer Formation, from more northerly basement rather than local sources. The rhyolite clast (Fig. 4.15) is interpreted as probable Permo-Triassic based on field observations and zircon ages.

Based on the almost monolithic nature of the schist and metamorphic quartz vein clasts, the conglomerate is interpreted as having come from a nearby basement source exposed during the Early Cretaceous Neocomian. The basement exposure may have resulted from the Triassic-Jurassic rifting that produced the intracratonic basins. Any significant transport distance would have created a much more heterolithic mix of fragments and probably have destroyed the friable schist fragments.

The sample from core hole CM10-247 of a much thinner (less than 1m) sandstone at the base of the Cuchillo at Sierra Santa Lucia appears to be the sandy residue from a different source than Mojina Las Vigas Formation (see Appendix A). It contains 3 Permo-Triassic zircons similar to Mojina, but it also contains 12 Neoproterozoic post-Grenville zircons with a mean of about 678 Ma, a population not seen at Mojina. Over half the population (53) of the zircon dates occurs between 1.6 and 1.7 Ga with a mean at about 1.652 Ga (Mazatzal) in contrast to the two zircons (1.7 Ga) detected at Mojina. The data at Sierra Santa Lucia most likely reflects a Mazatzal Province source that is believed to be more than 200km to the northwest. The thinness of the Las Vigas and lack of recognizable protolith here makes derivation of these zircons from reworked Scherrer a distinct possibility. Only two zircons reflect the prominent populations seen 30 km away at Mojina, particularly the Grenville and also lesser populations between 1.7 and 2.0 Ga. It is possible that these Mazatzal zircons are recycled from the Scherrer arkose.

The significant influx of clast of monolithic Granite-Rhyolite Province lithology would suggest that it is in part derived from a nearby source. The friable schist fragments could not have been transported far. The one 138.4Ma zircon although statistically unimportant is possibly from volcanism (Alisitos) contemporaneous with deposition of the Las Vigas Formation. The environment of deposition based on observations at Sierra Mojina, on the east margin of the Casas Grandes Platform (formerly known in the literature as the Aldama Platform but separated from Aldama by the Carrizal Basin), appears to be alluvial fans and braided streams shedding off the uplifted Precambrian basement to the west and filling the Carrizal Basin.

Cuchillo Formation (Kcu)

For this study the Cuchillo is divided into two members of which only the upper member crops out in the Cinco District along the west slopes of Sierra Santa Lucia. The lower member is cut by most of the drill holes in the same area. Both members crop out on the east face of Sierra Mojina (Fig. 4.8). The upper member suggests a deeper water macrofossil sparse environment while the lower member clearly indicates a shallow water environment with lagoonal mud hosting lagoonal patch reefs and periodic sabkhas both explained below.

The Upper Cuchillo Member of Sierra Santa Lucia is distinct from most published descriptions of the upper part of the Cuchillo Formation (for example Monreal and Longoria, 1999). It consists of dark gray (organic-rich fetid) limestone beds approximately 1 m thick with 10 to 20 cm thick shale partings with rare fossils and chert. Its lithology is similar to some descriptions of the Lower Benigno (Monreal and Longoria, 1999) except for its lack of fossils and chert. A review of the literature (Monreal and Longoria, 1999; Goldhammer, 1999; Humphrey and Díaz, 2003) suggests various possibilities for other correlations such as Upper Tamaulipas and Cupido Formations with the Upper Cuchillo of this study but offer no clear alternatives.

Monreal and Longoria (1999) point out that the Cuchillo Formation name has been applied in the literature to chronostratigraphic equivalent strata that are not lithologically equivalent. From their review of descriptions, the correlation in this study follows this suggestion and acknowledges a major difference in depositional environment between the two members. One possibility they did not address was the possibility that there is any deep water Upper Tamaulipas equivalent in northern Chihuahua as interpreted at Sierra Peña Blanca by Pingitore and others (1984) and Handschy and Dyer (1985). The main difficulty with these correlations is while they are using depositional environment correlations, they are using formational names from the Mexican Gulf Coast including the Abra Formation for the reef instead of the Aurora name that is more widely used in northern Mexico. Whether the presence of Upper Tamaulipas is a possibility or this is a distinct facies of the overlying Benigno or it is another previously unrecognized formation is beyond the scope of this study.

Lower Cuchillo (Kcul). The Lower Cuchillo Member is known only from drilling in the Pozo Seco area between Sierra Santa Lucia and Sierra Ruso in the Cinco de Mayo District but crops out on the east side of the Sierra Mojina area where half of the section is made up of diorite sills, leaving the strata poorly exposed (Fig. 4.8). The sabkha facies exhibit classic white recrystallized altered thin laminated stromatolitic carbonate beds with white recrystallized solution breccias (Figs. 4.16, 4.17) and birds eye textures (for example, Shinn, 1983). Some intercepts exhibit only a white laminated stromatolitic (leached or bleached) limestone. This alteration is attributed to the subaerial removal or chemical change of carbon and oxides that give most carbonates their color. Larsen (1977) used the term bleached for the white carbonate rock in the shallow lagoonal backreef of the Cambrian Bonneterre of southeast Missouri, locally referred to as “white rock”.

The sabkha strata is capped with collapse solution breccia (Fig. 4.18) that dominates in the lower part of the section. The collapse breccias project up to 60 meters above the sabkha deposits before resuming typical laminated shaly limestone stratigraphy. Cyclical transgressive and regressive episodes produced periodic subaerial exposure during which evaporites were formed during one regressive cycle and subsequently dissolved during later regressive cycle exposure. This periodic exposure and dissolution of the evaporites created weakly hematite stained collapse breccias made up of reduced laminated lagoonal mud fragments deposited during the periodic transgressive cycles. The fragments were then cemented by white sparry calcite. These breccias would then be buried by later transgressive lagoonal muds with sporadic bivalve-rich patch reefs. This cycle was repeated numerous times creating a repeated sequence of sabkha deposits overlain by collapse breccias, followed by more laminated black lagoonal muds with random patch reefs.

Black calcareous shale with sparse fossils dominates the upper part of the Lower Cuchillo. Multiple interbedded lagoonal mud-rich patch reefs (bioherms, Figure 4.19) dominate in the middle of the upper part of the Lower Cuchillo. The Lower Cuchillo has a drilling-indicated thickness of between 240 and 350 meters which could be structurally thickened or thinned by stacking or omission of section within the thrusted plates.

At Sierra Mojina the Lower Cuchillo is strongly intruded (up to 50% of the section) by coarse porphyry diorite sills. The sabkha and collapse breccia facies were not recognized at Sierra Mojina. Possibly they did not occur were not exposed or were intruded by the sills. However alteration from the diorite sills is very weak at Sierra Mojina.

Upper Cuchillo (Kcuu). The Upper Cuchillo Member at Sierras Santa Lucia (Fig. 4.20) and Sierra Mojina (Fig. 4.21) has been problematic in that it does not match with published descriptions. The unpublished, unlabeled (all location and source information removed) cross section attributed to Pemex on which initial stratigraphic nomenclature for the mapping was based includes this unit within the Benigno Formation, but its abundant shale partings is inconsistent with the literature and field observations of the

Benigno. Some authors (see Monreal and Longoria, 1999) reported similar lithologies in the Upper Cuchillo, but they also reported fossils not observed at Sierra Santa Lucia. Upper Cuchillo's almost total lack of visible fossils and chert, more typical of a transgressive deep water slope or basin deposits, is clearly distinct from the fossil- and chert-rich Benigno shallow water strata above and the shallow lagoonal mud, patch reef and sabkha strata below. Possible formations that may be lithologically correlative include the deeper water Upper Tamaulipas that is reported at Sierra Peña Blanca (Pingitore and others, 1984) and the Cupido Limestone as described by Humphrey and Diaz (2003).

The Upper Cuchillo Member consists of alternating 1 to 2 meter thick limestone beds interbedded with equal thicknesses of calcareous black shale which produces a distinctive stairstep appearance on the east side of the agate mine valley which separates the southern Sierra Santa Lucia into two main ridges (Fig. 4.20). Bedding plane thrust faults are abundant in the Upper Cuchillo so no complete unfaulted section of Upper Cuchillo has been measured or drilled, but an incomplete drilled section on the west side of Sierra Santa Lucia measured 550 meters. Based on additional drill holes this section appears thickened by a stacking of strata due to low angle thrusting as can be observed in outcrop.

An altered quartz porphyry sill intruded into the lower part of the Upper Cuchillo at Sierra Mojina (Fig. 4.22). This sill runs for six km along the southern half of the range and also is intersected in drill hole MOJ11-02 on the west side of Sierra Mojina opposite the mineralized area. This sill is thickest in the area of the mineralization which is concentrated as replacement in calcareous strata along both its upper and lower contacts. Recrystallization of the limestone associated with mineralization is also restricted to several meters from the contacts.

Aurora (Chihuahua) Group Ka

The Chihuahua Group is used variously as a substitute for the earlier used Aurora Formation or Group for the upper part (Albian) of the Lower Cretaceous carbonate section (Monreal and Longoria, 1999). The Aurora was used to group the carbonate strata when the shaly or marly formations such as Lagrima and Benevides were undistinguishable lithologically. In these cases subdivision of carbonate strata was made using paleontologic criteria. According to Monreal and Longoria (1999), this general definition commonly led to misuse of the Aurora term, whereas more rigorous usage of the newer Chihuahua Group terminology produced more precise stratigraphic correlations. On the basis of this observation Monreal and Longoria (1999) recommended dropping Aurora usage, but the Aurora Group or Formation is still the most common term encountered in the literature.

The Chihuahua Group includes, as defined by Monreal and Longoria (1999), the Lower Albian Benigno Formation, the Mid-Albian Lagrima and Finlay Formations (Fig. 4.23) and the Upper Albian Benevides and Loma Plata Formations. The Loma Plata Formation continues into the Lower Cenomanian and is capped by the Del Rio and Buda Formations in the Chihuahua Basin (Monreal and Longoria, 1999).

Benigno Formation (Kbg). The Benigno Formation consists of medium gray limestone with variable fossil content, variable black chert and minor shale partings (Fig. 4.24), very similar to the Finlay Formation. In the Cinco de Mayo district the Benigno is capped by a very distinctive strongly bioturbated carbonate mud transition zone from the Lagrima (Fig. 4.25). The Benigno limestone ranges from micrite to sparite but appears to contain less calcarenite and storm clasts than the similar Finlay. Thick reefal lenses dominate in the lower part of the Benigno Formation with bioturbated micrite to cherty micrite dominating in the upper part. The Benigno Formation is estimated between 200 to

300 meters thick in the field, with drill intercepts cutting 200 to 350 meters. Analysis of drilling results at Sierra Santa Lucia suggests the typical thickness is 250 meters.

The Benigno displays a rich biotic carbonate mud supported reefal environment at the base with rudists, pectins and oysters. It transitions cyclically from the carbonate mud reefs to slightly deeper sponge-rich environments (irregular black chert) throughout most of the section displaying minor above wave base periods with calcarenites and carbonate storm clasts.

The Benigno transitions upward into bioturbated lagoonal back reef, and finally into the deeper lagoonal facies of the Lagrima. The distinctive bioturbated top distinguishes the Benigno from the Finlay, but its greater thickness also aides in its recognition.

Lagrima Formation (Kl). The Lagrima Formation varies from black calcareous shale to dark gray argillaceous limestone and is variably fossiliferous with pelecypods and gastropods (Fig. 4.26). In surface mapping, its slope-forming nature and its favoring grass over brush as a ground cover makes it a distinctive map marker horizon between the blocky brush-covered Finlay and Benigno limestone units (Fig. 4.23). It is easily recognized in both the field and in imagery.

Measured thicknesses are greatly affected by structure and ranges from 30 to 150 meters, but drilling indicates a true thickness of about 70 meters in the Sierra Santa Lucia. The dark calcareous shale lithology dominates, but some drill holes have intersected thin bedded (~10 to 20 cm) limestone in the same stratigraphic horizon in marked contrast to the thicker bedded Finlay above and the Benigno below.

In the Santa Eulalia area to the southeast (Fig. 4.5), the Lagrima is a limestone more typical of the Aurora of the Coahuila Platform. Some Servicio Geologico Mexicano maps persists with the central Texas name Walnut Formation for strata chronologically equivalent to the Lagrima Formation (Cedillo and others, 1998).

Finlay Limestone (Kf). The Finlay Limestone mostly consists of medium gray limestone with variable fossil content and variable black chert and is very similar in appearance to the upper part of the Benigno (Fig. 4.27). Black shale partings are thin but create a ledged appearance in outcrop. Locally, reef facies appear to be aerially restricted patch or linear reefs with lime mud matrices of low permeability. The carbonate ranges from micrite to sparite and calcarenite. Various above-wave-base calcarenites occur in the Finlay section, but 10 to 20 meters below the top of the Finlay limestones lies an extensive breccia zone (Figs. 4.28; 4.29). Along this breccia horizon remnants of a zone of randomly oriented flat plates of carbonate mudstone can be seen. They are interpreted to have been ripped from the shallow sea during a major storm that produced wave troughs that greatly exceeded the normal wave base (Charles Kerans, personal communication). This created a widespread horizon of significantly increased permeability, that by dissolution appears to have produced the extensive solution breccia zone below the upper 10 to 20 m of Finlay limestone. Lateral variations such as transitions to carbonate sand and complete absence of the horizon have been observed in drilling. Currently this horizon is indicated by mostly hematite rich to stained, residue filled solution cavities, abundant coarse white calcite, chalcedony-quartz deposits and metallic sulfide mineralization. The actual original thickness is not known because of solution; but where it is preserved, it is approximately 1 meter thick. These preserved zones were probably the thinnest with lower than normal permeability and the 10 m thick zones of solution breccia are probably thicker than the original rip up clast zone because of the dissolution of the adjacent limestone created larger cavity. Early during the exploration program the silicified breccia was interpreted as a solution breccia along a flat fault. The breccia zone was always near the top of the Finlay and not the most logical place for a flat fault compared to the Finlay-Benevides contact. Not until partially dissolved remnants of the storm rip-up clasts were observed in drill hole intercepts (CM09-106 at 744m, CM09-122 (Figs. 4.28 and 4.29) at 583m and CM09-124 at 511m; and later confirmed in CM11-384 at 199.5m and CM12-401 at 164.7m) was its true stratigraphic character recognized and interpreted to be a zone of storm rip up clasts (see Shinn, 1983, Figure 26). Several zones at the same position in the Finlay exhibited fossil hash and carbonate sand (CM09-135 and CM09-148). Thickness of the Finlay Limestone ranges from about 100 to 200 meters with 150 meters being most typical. As usual, structure can lead to great variation in the intercepted value. The upper contact with the Benevides is usually more gradational than the lower contact with the Lagrima.

The Finlay in many ways is almost identical with the Benigno, but the bioturbated top of the Benigno is definitive of the formation. The Benigno is typically thicker than the Finlay (200 to 300m) but structural complications can make this unreliable. The solution cavity, calcite filling, silica filling and mineralization are almost universal near the top of the Finlay but are rare in the Benigno. Rare cavernous solution cavities have been encountered along bedding and cross cutting structures in both the Finlay and Benigno.

Benevides (Kbv). The Benevides Formation ranges from a black to dark gray calcareous shale (Fig. 4.30) to a medium gray argillaceous nodular limestone sequence (Fig. 4.31) that is variably fossiliferous (Fig. 4.32). Several zones of the Benevides unit are more calcareous than others including the approximate 100m above the Finlay. The limestone units could represent lateral time equivalents of many other formations, including Loma Plata, Del Rio and Buda Formations. Locally these formations display much higher shale content than to the southeast in the Chihuahua City area and probably represent a transition between the Bisbee Group clastic environment to the northwest and the more massive carbonate Aurora section observed to the southeast. Drilling intercepts suggest thicknesses on the order of 300 to 400 meters, but the complex variation of dip indicates probable thickening by extensive internal folding within the formation. The alternation of dark gray calcareous shale with light gray micritic limestone on the scale of tens of meters defines the formation in drill core.

The Benevides is the lateral equivalent of the Kiamichi Formation of Oklahoma and the Kiamichi name was used in early studies of the Chihuahua Basin. The SGM continues to use Kiamichi in its maps (Hernandez-Velazquez and others, 2002). The Benevides Formation is underlain transitionally by the Finlay Limestone and is typically separated from the overlying Indidura by a major bedding plane fault at Sierra Santa Lucia, but some Indidura is found beneath the fault plane. Mapping on the Casas Grandes Platform to the west of Sierra Ruso indicates that Indidura over Benevides is a normal sequence in this area.

Loma Plata (Klp). The Loma Plata Formation (misnamed Loma de Plata in Pemex and some SGM maps) overlaps the Lower Cretaceous-Upper Cretaceous boundary. The Loma Plata has not been observed in the Cinco de Mayo district but caps the southwest ridge at Sierra Banco Lucero (Figs. 4.5; 4.7). Banco Lucero is the only confirmed locality of Loma Plata west of the Florida-Aldama Ridge.

The Loma Plata forms a massive limestone bluff above what was mapped as Benevides for this study, but Rodriguez-Torres and Guerrero (1969) gave the local name of Ahumada Formation. Monreal and Longoria (1999) confirm the Ahumada Benevides correlation. The Loma Plata Formation displays black banded chert similar to the time equivalent Treviño or Georgetown Formation on the Coahuila Platform.

Upper Cretaceous- Cenomanian.

The Upper Cretaceous section in the Chihuahua and Carrizal Basins of north central Mexico consists of Cenomanian Upper Loma Plata Formation, Del Rio Clay, Buda Limestone, Indidura and Ojinaga Formations. The Loma Plata Formation is only recognized currently in Sierra Banco Lucero and as yet the Del Rio and Buda Formations have not been observed in the Carrizal Basin. The Late Cenomanian Indidura was confirmed in this study as the first occurrence of significant quartz sand and silt above the Las Vigas Formation. The Ojinaga Formation is defined mostly in the Chihuahua Basin but is recognized in the Carrizal Basin. It is recognized in this study as a thick sequence of red to green mudstones alternating with quartz and volcanic sandstones. Scattered conglomerate beds containing coarse volcanic and intrusive debris. The Indidura Formation consists of thinly laminated fine-grained sand, silt and black mud layers. It is combined with the Ojinaga formation in some studies (unpublished Pemex reports).

Indidura Formation (Kin). The fine sand and silt of the Indidura (Fig. 4.33) represent the first significant detrital quartz grains in the stratigraphic section above the Las Vigas Formation at Sierra Santa Lucia. HCl digestion of sand in the Benevides left only radiolarian tests as a residue after dissolution of the minor carbonate sand beds observed in the formation. HCl digestion of the Indidura revealed abundant sand size quartz and volcanic rock grains. The Indidura Formation displays only millimeter scale laminations of fine sand, silt and black shale. Fossils have not been observed in the Indidura in the Sierra Santa Lucia area. Formation thickness has not been constrained for the Indidura in this area as the formation is highly disrupted by bedding plane faulting and shearing. The correlation of local outcrops with published occurrences of Indidura (unattributed PEMEX correlation table) is based on stratigraphic position and lithologic character.

South of the Coahuila Platform the Indidura is much less sandy but still displays the characteristic millimeter scale laminations of shale and lime mud and lack of fossils. This lithologic difference makes the use of the name Indidura technically incorrect in this area, but it is variably used in the Chihuahua Basin and appears to be chronostratigraphically equivalent.

Ojinaga Formation (Ko). The Ojinaga Formation is defined in the Chihuahua Basin but continues westward into the Carrizal Basin. There it is recognized as a thick alternating sequence of red to green mudstones alternating with quartz and volcanic sandstones (Fig. 4.34) with scattered conglomerate beds Fig. (4.35) containing quartz, and volcanic and coarser igneous debris (Fig. 4.36). Individual beds range from 2 to 20 meters thick. The Indidura Formation consists of thinly laminated fine-grained sand, silt and black mud layers. From the review of stratigraphic sections compiled in unpublished Pemex reports, the Indidura is sometimes combined with the Ojinaga Formation and in other studies the Indidura name is applied to the entire Ojinaga sequence.

GEOLOGY AND MINERALIZATION OF SIERRA SANTA LUCIA (CINCO DE MAYO DISTRICT)

The Cinco de Mayo District located in Sierra Santa Lucia (Fig. 4.37) was the first detailed study (mapping for MAG Silver, 2007-2010 and core logging 2007-2012) in this region that led to the definition of the Carrizal Intracratonic Basin.

Introduction

The Cinco de Mayo mineral district has a long history of mineral exploration with only minor actual production. Historic exploration was carried out by shallow prospect pits and shafts. One of the deeper shafts at the north end of Cerro Cinco de Mayo actually cut the south end of what is now known to be the main carbonate replacement deposit in the district, the Jose Manto.

The first known exploration drilling was a six hole program by Peñoles in 1996, mostly on the west side of the district. They focused on massive white quartz veins that cut the mostly hanging wall of what is now known to be Pozo Seco molybdenum deposit. The map produced by Peñoles was principally alteration and quartz vein mapping focused on the silicified zones west of Pozo Seco and at the northeast end of Sierra Santa Lucia.

Mapping was started for this project in 2007 with observation of in-progress drilling core to better understand stratigraphy observed in the field. As mapping continued into 2008, the author was given more responsibility to maintain consistency of formation determination both by logging the core and training new geologists. Through 2012, the author logged formations, alteration, major structure and anomalous features of 207,160 m from 426 core holes (27 of which ranged from 900 to 1,200 m deep) and formations and alteration from chips representing 1,097 m of rotary drilling from 11 holes. This mapping and logging has produced a reliable and productive understanding of the structure and mineralization of the district.

Previous work

The stratigraphic base presented earlier was primarily established by this mapping aided by two unpublished Pemex cross sections through the southeast ridge area. The reviews of Chihuahua Basin stratigraphy by Monreal and Longoria (1999) and of the sequence stratigraphic setting of the Mesozoic of northern Mexico by Goldhammer (1999) were particularly helpful along with other references cited.

No useful published or unpublished district scale maps are known, but two unlabeled cross sections reported to have originated in Pemex appear to accurately portray a large fault-bend fold along two closely spaced cleared lines interpreted to be proposed seismic lines cutting the property. The cross sections appear to only reflect surface data generated before any seismic was available and may have been preparation for a seismic line. The only known published map of Sierra Santa Lucia is the 1:250,000 scale Nuevo Casas Grande map of SGM (Hernandez-Velazquez and others, 2002) that lacks useful detail at this scale (Fig. 4.38). Only one inferred thrust fault was mapped and no stratigraphic offset was indicated on it. An exploration map of unknown origin or date recognized important elements of structure and lithology but made no stratigraphic correlations. Mapping by Peñoles focused on the silica alteration in the western Pozo Seco area but ignored the geologic setting and major structure.

Sierra Santa Lucia (Cinco de Mayo District) Structure

This study determined that Sierra Santa Lucia structurally consists of a series of three main plates stacked against the margin of an undeformed platform which appears to contain the same undeformed Upper Cretaceous stratigraphy (Figures 4.39, 4.40a and 4.40b) as the out-of-the-basin thrusting from the east. The stacking of three plates results in repetition of a large part of the Aurora Group (Chihuahua Group) carbonate section (Fig. 4.41). A contour of the top of the Finlay Limestone (Fig. 4.42) in the northern extent of Sierra Santa Lucia illustrates the plunging of this surface to the northeast in each of these three plates. The Finlay top in the Pozo Seco thrust sheet diplays a northwest strike with an upward warp from initial pre-thrust folding along the Polaris Fault. The Celia thrust sheet to the southeast displays a similar northwest strike but turns more to the north-northwest as the beds steepen on the back side of the fault bend fold.

The Finlay in the Jose thrust sheet is 300 m above the same contact in the Celia thrust and it maintains the northwesterly strike as opposed to the more northerly strike in the Celia thrust.

A fourth plate, Sierra Ruso, has been documented by drilling to be a isoclinally folded, detached gravity glide block that came off the top of the over-steepened stack of thrust plates. Mapping shows that the southeastern ridge of Sierra Santa Lucia is a recumbent fold with the axial plane exposed in the Upper Cuchillo Formation (Fig. 4.43). Drilling has determined that the Sierra Ruso glide block is the nose of a recumbent fold with its axial plane in the Benigno Formation. Sierra Ruso formed as the nose of this recumbent fold passed the crest of the fold in the Cuchillo Formation and broke from the easternmost plate and moved westward to its present position on the stable platform as gravity glide block (Fig. 4.44).

Multiple bedding plane faults were mapped in the Upper Cuchillo Formation along the northwest side of Sierra Santa Lucia with the most obvious being highlighted by a fault-bend fold in the upper plate (Fig. 4.44). None of these plates displays recumbent folding further supporting the link between the southeast thrust plate and Sierra Ruso.

The district cross section (Fig. 4.41) also shows the deep synclinal troughs of Upper Cretaceous Indidura and Ojinaga Formation. This syncline that is completely covered by alluvium was first observed in a low level aeromagnetic survey flow by MAG Silver. Remagnetization of iron-bearing grains in the sandstone beds and pyrrhotitization of syngenetic pyrite after folding produced a strong magnetic image of the folded Ojinaga.

A second syncline of Indidura and Ojinaga crops out in the northeast corner of the district map. Although alluvium covers the divide between the two synclines, two drill holes intersected Benevides in a fold or thrust between them confirming that they are two separate synclines.

Cinco de Mayo District Mineralization

Two major new discoveries have resulted from the work carried out in the district by MAG Silver Corp. and their agents in Mexico Minera Cascabel S.A. de C.V. Exploration details can be found on MAG's web site www.magsilver.com. This study was a major component contributing to success of the project through developing structural models and building a stratigraphic framework necessary to maintain stratigraphic consistency in the 208,257 m of core and chips from the 437 exploration drill holes on the property. All of the products of this drilling were logged by the author.

The Jose Manto is a new Ag-Pb-Zn discovery located in the uppermost of three stacked thrust plates along the west margin of the newly described Carrizal Basin (Figs. 4.39 and 4.46). Along the west side of Sierra Santa Lucia that consists of two of these stacked thrust plates, the Pozo Seco oxide Mo-Au system was discovered in the basal fault of the large gravity glide block that forms the Ruso hills (Figs. 4.39 and 4.46).

Jose Manto. Prior to the present exploration program a number of small mines on mantos and veins were scattered along the east side of the Santa Lucia range from the isolated Orientales mine north of the main range to several scattered mines at the north end of the range followed by prospect pits all along the east side of the range. Cerro Cinco de Mayo occurs in the valley 1 to 1.5 km in front of Santa Lucia and contained some of the more encouraging old mines in mantos in the Finlay as indicators of exploration potential. Prospects and small mines continue down the east side of the range. The first exploration effort focused around the old mines at Cinco de Mayo hill, then shifted to along the northern range front where an almost continuous ridge of silicified breccia cropped out along the top of the Finlay Limestone that was originally considered to be the mineralized expression of another thrust fault. Drilling along the eastern range front showed that the alluvial valley between Cinco de Mayo hill and the main range was underlain by Benevides Formation under a thin layer of alluvium. During the second phase of drilling the silicified breccia was determined to be within the upper part of the Finlay Limestone (10 to 20 m below the top) and probably was not the replacement of a fault breccia as originally interpreted from surface mapping. As described under the stratigraphy section this favorable zone for mineralization currently is interpreted to be a bed of storm rip-up clasts that created a very widespread permeable horizon favorable for the later transport of mineralizing fluids.

Drill hole CM07-09, just north of Cerro Cinco de Mayo, ended in hornfelsed Benevides and probably stopped within 100m of mineralization in the permeable horizon. Drill hole CM07-20, 1.5 km WNW of drill hole 9, is considered to be the discovery hole (Fig. 4.47).

Alteration includes retrograde chloritized hornfels and scheelite-bearing hydrogrossular garnet-bearing skarn (Peter Megaw, personal communication) of the Benevides Formation (Fig. 4.48) and recrystallization and garnet skarn in the Finlay Limestone. The skarn is documented from drilling to continue for 1,350m along strike in the central part of the mineral system and contains variable scheelite throughout as determined by UV light (Fig. 4.49) and confirmed by assays. The massive sulfide manto replacing the rip-up clast zone in the Finlay Limestone continues for over 3,000m along strike. The manto continues through the centrally located skarn zone that mostly affects the Benevides Formation, but the Finlay is also subject to recrystallization and skarn development. The mineralization in the rip-up clast manto has been documented over 600m vertically and is open at depth (Fig. 4.50). Other local controls of mineralization consist of other permeable zones within the Finlay, structures and the upper and lower shale contacts which act as aquitards to mineralizing fluids.

The thrust sheet that forms Cerro Cinco de Mayo, named in this study the Jose thrust sheet, continues WNW from the NW end of Cerro Cinco de Mayo as a blind thrust under alluvium because the fault-bend fold at the nose of the Finlay Limestone does not reach the surface and the overlying Benevides was easily eroded. This thrust slice dips steeply and forms back thrusts where the sheet becomes overturned and thrusts back to the NNE (Fig. 4.51).

Pozo Seco Mo Oxide Breccia. The other poorly exposed mineral system that has been extensively explored is the breccia hosted Pozo Seco Mo-Au deposit that consists mostly of powellite druses coating silicified breccia fragments of the hosting Upper Cuchillo Member. This deposit appears unusual as most other known powellite deposits occur as minor oxide zones above deeply formed molybdenite deposits (Mineral Data Publishers, 2005). There is no evidence at Pozo Seco of a molybdenite-bearing sulfide system being the source of the powellite. The silicified breccia hosting the mineralization within the Upper Cuchillo Member is not exposed at the surface nor are there any significant grades exposed. Neither the rock nor white quartz exposed along low angle faults cutting the Upper Cuchillo reveal geochemical evidence of the underlying deposit. Quartz veins, some up to 5 m across, trend through the broader area west of the deposit that terminate at the west edge of the mineralization. Peñoles focused their 1996 mapping and drill testing on the area of quartz veins, missing the powellite mineralization. The molybdenum-bearing solutions appear to have risen along the fault under the Sierra Ruso glide fault with a root like feeder rising along it (Fig. 4.52). Contouring the surface between the Upper and Lower Cuchillo Members also indicates that the ore body is also situated along the crest of an antiform along the east edge of the fault.

The powellite is easily logged with the use of a shortwave UV lamp producing a pale yellow orange white fluorescence. The intensity of this fluorescence was found to correlate closely with Mo assay values.

The mineralizing solutions appear to have risen along the base of the gravity glide fault that forms a root zone along the west side of the deposit and spread laterally into the adjacent Upper Cuchillo that had been extensively brecciated in a large body projecting horizontally from the fault zone (Fig. 4.52). The ore was concentrated in stacked horizontal sheets within the breccia body. The most commonly observed form of the mineralization are light and dark brown banded coatings on the breccia fragments. The mineralized sheets give the appearance of phreatic surfaces that varied over time where boiling was resulting in the precipitation of the powellite.

SIERRA MOJINA GEOLOGY

Previous work does not appear to include mapping beyond the SGM Buena Aventura H13-7, 1:250,000 scale geologic map (Cedillo C. and others, 1998). Field trip visits and radiometric ages from igneous clast samples from the Las Vigas were all that were found in the literature. In addition to the complete Lower Cretaceous section from the Las Vigas through Lower and Upper Cuchillo, Benigno, Lagrima and Finlay, a propylitically altered arkosic mudstone with altered caliche nodules underlies the Las Vigas and a non-fossiliferous limestone underlies the arkose (Fig. 4.54). The arkose and limestone have been tentatively identified as the Permian Scherrer Formation which is known for arkosic silty mudstones and fossil-poor limestones (Blakely and Knepp, 1989). The arkosic mudstones are identical strata to that observed beneath the Cretaceous section in core in the Pozo Seco area of Sierra Santa Lucia. The limestone observed at the base of the section at Sierra Mojina was not intersected in the drilling at Sierra Santa Lucia.

Structurally Sierra Mojina is underlain by an inverted Permian basement block and the Lower Cretaceous strata form a fault-bend fold over this inverted basement block (Fig. 4.55). Dips in the east face of the range in the Mojina Mine area range from 5 to 10 degrees. Drilling indicates that the beds begin to roll over steeply (in excess of 45°) in the nose of the fault-bend fold on the west flank of the range west of the mine (Fig. 4.55). In the north part of the range the Finlay, Lagrima and Benigno cap the range with 20 to 30° dips, that steepen to near vertical on the west flank of the range where they end at a flat fault underlain by flat-lying Finlay below the nose of the fault-bend fold (Figs. 4.56, 4.57).

Mineralization at Sierra Mojina occurs as replacement along the upper and lower recrystallized contacts with an altered aphanitic felsic sill intruded into the Cuchillo Formation. Thickness, up to 100m, as well as alteration are greatest in the Mina Mojina area. The sill projects for approximately 5 km along the range front and is only a few meters thick at its distal north and south ends.

PREVIOUS WORK

Following the Permo-Triassic suturing of the Americas, a Late Triassic to Mid-Jurassic extensional event split Mexico into a series of parallel basins and platforms. Two parallel basins the Sabinas Basin and Mexican Sea (Fig. 4.3) have been proposed (Burckhardt, 1930 and Humphrey and Diaz, 2003 mostly a reprint of a 1956 paper by Humphrey in recognition of its importance to the stratigraphy of north-central Mexico). The Mexican Basin was projected into northeastern Chihuahua (Humphrey, 1956; Humphrey and Diaz, 2003), but the northern part was renamed the Chihuahua Trough by

DeFord (1964). The Mexican Basin was renamed San Pedro de Gallo Basin by later PEMEX geologist (Garza G, 1973), but this attempt failed in broader literature and the Mexican Basin (or Sea or Mar) name continues as the most widely used in recent studies (Haenggi and Muehlberger, 2005). In the past, the focus has been on one extensional basin in Chihuahua between the North American Craton of west Texas and the Aldama platform (Fig. 4.4) of northwest Chihuahua (Haenggi, 2001, 2002; Haenggi and Muehlberger, 2005).

Most of the literature on the northern part of the state of Chihuahua limits the Chihuahua Basin to a narrow belt along Chihuahua's border with Texas (Hennings, 1994; Haenggi, 2001, 2002; Goldhammer, 1999). The more generic term basin will be used here instead of trough that was more commonly used to signify a down-warped depression in geosynclinal theory rather than an extensional basin (Bates and Jackson, 1987). This also has led to confusion when other authors have applied the term trough to other basins of the region. Haenggi's extensive compilations (2001, 2002; Haenggi and Muehlberger, 2005) on the Chihuahua Basin broadened the definition to include evidence of a thickened basin sequence to the west in the northern part of Chihuahua, but he maintained the Aldama Platform as the west edge of the Chihuahua Basin in the central part of the state (Fig. 4.4). Haenggi (2002) generated an isopach map of the basal Cretaceous La Vigas Formation by compiling data from various measured sections and PEMEX drilling data (Fig. 4.4). This isopach map implied at least a partial ridge dividing two major thickenings of the Las Vigas.

The stratigraphy of the previously unrecognized basin to the west has not been specifically addressed in the literature other than as a part of 1:100,000 scale quadrangle mapping in the Banco Lucero-Alcaparra areas (Rodriguez-Torres and Guerrero, 1969) and the Nuevo Casas Grandes H13-4 1:250,000 H13-4 geologic quadrangle (Hernandez-

Velazquez and others, 2002). Monreal and Longoria (1999) made tentative correlations between Banco Lucero and the Chihuahua Basin stratigraphy. Hernandez-Velazquez and others (2002) did not use the stratigraphic nomenclature of Rodriguez and Guerrero (1969), but their own mixture of Mexican and Texas stratigraphic nomenclature. Their stratigraphic column at Sierra Banco de Lucero does not match the ages assigned by the other authors but also appears to contain an error with the Loma Plata being erroneously labeled Edwards placing it over Kiamichi (Benevides) resulting in an inverted section.

Haenggi (2001,2002) proposed the Chihuahua Basin was a complex of pull-apart basins (Fig. 4.4) as an extension of those proposed in west Texas by Muehlberger and Moustafa (1984). DeFord (1958) recognized that the Chihuahua Basin was an inverted basin. Haenggi (2002) and Haenggi and Muehlberger (2005) focused on linear features that might reflect the grid of proposed pull apart basins, but did not include any documentation of the basin inversion model. The bidirectionality of thrusting in the Chihuahua Basin between Aldama and Ojinaga was recognized by Hennings (1994) and attributed to the presence of evaporitic strata in the section. The isopach map of the Las Vigas basal sand and conglomerate from measured sections and Pemex drilling (Haenggi, 2001) along with a Chihuahua Basin cross section (Monreal and Longoria, 1999) highlight the possible presence of a structural ridge on the west side of the Chihuahua Basin. Eguiluz-de Antunano (1984) proposed a north-trending strikeslip fault that according to Haenggi (2002) corresponds to the boundary between two different orientations of folds within the Chihuahua Basin. This boundary also corresponds to the thinning shown by the isopach of the Las Vigas Formation (Fig. 4.4, Haenggi, 2002; Haenggi and Muehlberger, 2005).

SIERRA BANCO DE LUCERO GEOLOGY

Sierra Banco Lucero (Fig. 4.7) is located in northern Chihuahua, approximately half way between Sierra Santa Lucia and Samalayuca. It is a southeast-trending pair of ridges with bedding that dips approximately 10 to 20° to the southwest (Fig. 4.58). The range was first mapped by Rodriguez and Guerrero (1969). They did not recognize the section as correlating with regionally known strata and gave local names (Lucero and Ahumada formations) to all strata below the Loma Plata Limestone at the exposed top of the Lower Cretaceous section. Monreal and Longoria (1999) indicated that the Lucero Formation is Upper Aptian and Lower Albian based on the fossil evidence. The author mapped it as Upper Cuchillo based on stratigraphic position and lithologic correlation with the Upper Cuchillo of Sierra Santa Lucia that is also Upper Aptian to Lower Albian in their stratigraphic column (Monreal and Longoria, 1999, see Fig. 4.6). The Ahumada was assigned as Upper Albian by Guerrero (1969) but Lower Albian by Monreal and Longoria (1999). I mapped it, based on lithologic correlation and stratigraphic position with Sierra Santa Lucia, as Upper Albian Benevides Formation. Monreal and Longoria (1999) were not aware of the ramp fault and may have sampled Upper Cuchillo (Lucero of Rodriguez and Guerrero 1969) below the fault thinking is was part of the Ahumada of Rodriguez and Guerrero (1969).

Rodriguez and Guerrero (1969) also did not recognize thrusting exposed as a low angle ramp fault cutting from the top of the Upper Cuchillo across the Benigno, Lagrima, Finlay and most of the Benevides. Hernandez-Velazquez and others (2002) (Fig. 4.59) recognized the thrust fault between the southwest ridge and the northeast ridge but placed Edwards (Finlay of this study) over Kiamichi (Benevides of this study) in the southwest ridge and Edwards over Walnut in the northeast ridge. Beside the use of Central Texas terminology Hernandez-Velazquez and others (2002) imply an overturned section in the southwest ridge of Banco Lucero.

This mapping (Figs. 4.60, 4.61) observed a normal Cuchillo, Benigno, Lagrima and Finlay (Edwards equivalent) section below the thrust fault in the northeast ridge and the Benevides capped by Loma Plata (Georgetown equivalent) in the southwest ridge. The Loma Plata Formation is common in the Chihuahua Basin but has not been mapped elsewhere in the Carrizal Basin.

As previously noted the primary source of previous mapping difficulties lies with the fact that the thrust fault cuts out the Chihuahua Group (Finlay, Lagrima and Benigno) at the southeast end of the range where a thick section of Benevides lies on top of the fault (Fig. 4.61). Along the strike of the range the thrust fault migrates up section to the northwest in both blocks exposing a Benigno-Lagrima-Finlay sequence southwest of the high bluff of Banco Lucero (Benigno Formation) but cutting out most of the Benevides in the upper plate in the same location. The southeast end of the range contains limited outcrops of the Benigno strata of the Chihuahua Group and lacks the overlying Lagrima and Finlay Formations. Good exposures of the Lagrima and Finlay occur along the northwest end of the northeast ridge, southwest of the prominent peak formed of Benigno Limestone (Fig. 4.61).

CARRIZAL REGIONAL RECONNAISSANCE

A number of project areas produced limited mapping or documentation of the structural setting of the projects. South-southeast of Sierra Mojina, north of Chihuahua City, three project areas expose thrusting out of the Carrizal Basin. The Terrazas area (Rio Tinto) is located 40 km north of Chihuahua City on the east side of the valley north of the city (Fig. 4.62). Salamex is 41 km north-northwest of the city, and Descubridora Mine 7.5 km north-northeast from the city center, within the city.

The Terrazas (Rio Tinto) Project Area

The Terrazas area consists of copper skarn in an undated limestone that based on regional stratigraphic studies should be older than Late Cenomanian. In outcrop it appears to be thrust to the east over Upper Cretaceous siliciclastic strata that is only weakly affected by the alteration near the fault and is not mineralized. Various abandoned mines appear to project down only as far as the fault implying that mineralization does not continue below the fault in those areas either. The east-directed thrusting or other structural effects of tectonic shortening were not observed in the Sierra Peña Blanca Lower Cretaceous limestones to the east. Padilla-Palma and others (1997) indicated a gentle fold along the crest of the Sierra Peña Blanca, but the author only observed block faulting in the Sierra Peña Blanca Lower Cretaceous limestones

The important observation at Terrazas is that the carbonates that correlate lithologically with the Benigno through Finlay Formations are in east-directed thrust plates, thrust over calcareous shale that displays a strong lithologic correlation with the Benevides Formation. This indicates thrusting out of the Carrizal Basin onto the Aldama-Florida structural ridge and further indicated that the basin is continuing south from the last observed location at Sierra Mojina on the west side of the Florida-Aldama Ridge.

Descubridora Mine area Chihuahua

The Descubridora mine was located under the Chihuahua City sanitary landfill on the northeast side of the city (Fig. 4.63. At the time of mapping in 1992, the mine was accessible, but it is assumed that continued landfill development may have cut off access. Mining activity had excavated large underground chambers on the scale of 100’s of meters in both length and height in the Aptian-Albian limestones. These chambers revealed east-ramping thrust faults that were also exposed on the surface. These north-striking west-dipping flat faults located on the surface were accentuated by tufficite sill-like bodies intruded into the fault planes. The thrusting is east-directed as at Terrazas. The volcanic cover limited mapping of the limestones, and they were mapped before the current level of understanding of the Lower Cretaceous was achieved. Based on current knowledge, the limestones mapped were part of the Lower Cretaceous Benigno through Finlay strata.

The apparent east-directed thrusting is consistent with the Terrazas thrusting observed to the north. Additional east-directed thrusting was observed in the field between these two prospect areas.

Cuauhtémoc, Chihuahua (Salamex Prospect)

The village of Cuauhtémoc lies on the west side of the valley north of Chihuahua City west-southwest of the Terrazas area on the opposite side of the valley. Several occurrences of Aurora (Chihuahua) Group limestone crop out in the low hills east of the village. Along the east side of the main north-trending drainage through the village of Cuauhtémoc a distinct west-southwest-directed fault bend fold crops out (Fig. 4.64). This fault bend fold reveals the only indication of the direction of motion. This west-directed fault bend fold indicates thrusting along the west side of the Carrizal Basin as opposed to the interpreted east-directed thrusting observed along the east side of the valley at Terrazas and Descubridora.

CARRIZAL REGIONAL CROSS-SECTION

In addition to the mapping at Sierra Santa Lucia and Sierra Mojina reconnaissance mapping of the Cretaceous was carried out from Sierra Los Arados to the east of Sierra

Santa Lucia and north northeast from Sierra Santa Lucia to Sierra Banco Lucero and on to Sierra Samalayuca (Fig. 4.65). Various other mapping projects began in the 1990's for Minera Kennecott including Descubridora, Rio Tinto (Terrazas) and Sierra Los Arados; continuing in 2008 for MAG Silver at Salemex (Fig. 4.64). Additional reconnaissance mapping was carried out individually by the author at Sierra Samalayuca, Banco Lucero and intervening areas to supplement the company defined projects. All of this work combined with extensive literature reviews led to the structural definition of the Carrizal Intracratonic Basin. The data allows creation of a diagonal cross section from the Casas Grandes Platform across the newly defined Carrizal Basin and on to the Florida-Aldama Ridge and ends at the west margin of the Chihuahua Basin at Samalayuca (Fig. 4.65 and 4.66). Further reconnaissance mapping south from Sierra Mojina to Terrazas and on to Chihuahua City confirms the continuation of the Carrizal Basin with thrusting occurring bidirectional both out-of-the-basin to the east on the east side of the valley and west-directed thrusting on the west side of the valley.

This cross section (Fig. 4.65 and 4.66, includes mapping of Figure 4.40a and the cross section in Figure 4.41) has no vertical exaggeration and is divided into two halves. Figure 4.67 (geologic map) and Figure 4.68 (cross section) permit a better view of the geology of the southwest half of the cross section and Figure 4.69 (geologic map) and Figure 4.70 (cross section) for a better view of the northeast half of the cross section, both at better scales.

Figure 4.68 indicates the out-of-the-basin thrusting on to the Casas Grandes Platform to the west at Sierra Santa Lucia followed to the northeast with two isoclinal synclines of Upper Cretaceous Indidura and Ojinaga separated by an anticline of Benevides. The westernmost Upper Cretaceous syncline has no outcrop but is well defined by draped aeromagnetic data and extensive drilling. The Benevides anticline is known only from drilling. The second syncline of Upper Cretaceous strata crops out at the base of the volcanic rocks on the northeast side of the Sierra Santa Lucia map area. To the north-northeast of the Sierra Santa Lucia map area comparatively gentle folding in the middle of the basin and less intense thrusting out-of-the-basin to the northeast on the east margin of the basin at Sierra Banco Lucero occur (Figs. 4.69, 4.70). Outcrops are limited to the Upper Cretaceous on the Florida-Aldama Ridge and dips of 15° are the maximum observed in these limited outcrops. Finally at Sierra Samalayuca (Fig. 4.11), an anticlinal inverted basement block of interpreted Permian age overlain with the Upper Jurassic La Casita Formation (identified by ammonites Monreal and Longoria, 1999: disputed by Young, (in Haenggi, 2002) defines the west margin of the Chihuahua Basin.

Despite the extensive volcanic cover found from Sierra Santa Lucia south, small windows in this cover expose east-directed thrusting mapped at Terrazas (40 km NNW of Chihuahua City, Figure 4.71) and west-directed thrusting mapped at Cuauhtémoc (40 km NW of Chihuahua City) suggest that the fold and thrust belt last observed at Sierra Mojina reflects that the Carrizal Basin continues into the Chihuahua City area under volcanic cover.

The Florida-Aldama Ridge becomes exposed again in the platform carbonates of Sierra Peña Blanca and Sierra del Cuervo where Permian and Precambrian rocks crop out NNW of Aldama. The ridge continues south under the platform carbonate section in the Santa Eulalia District where it disappears under volcanic cover at the south side of the district.

DISCUSSION: CARRIZAL-MEXICAN BASINS

A better understanding of the structural configuration of Cretaceous strata in the north central part of the state of Chihuahua has led to a more precise delineation of the

Jurassic intracratonic basins. The recognition of the newly defined Carrizal Basin resulted from this improved basin delineation. Bidirectional thrusting out of each individual basin produced during tectonic shortening as seen between Sierra Santa Lucia and Banco Lucero, and Salemex and Terrazas is the principal defining structural element of the basins. Relatively undeformed Cretaceous strata as well as basement exposures define the stable platforms adjoining the basins. Basement exposures and drill core in inverted basement blocks strengthen the definition of the platform margins.

A bidirectional fold thrust belt continues from Chihuahua City north to Banco de Lucero where it turns more northwesterly into the bootheel of New Mexico. This fold-thrust belt defines a previously unrecognized basin now named the Carrizal Basin for the village of Carrizal 15 km west-southwest of Villa Ahumada and 150 km south-southwest of Ciudad Juarez (Fig. 4.).

The Carrizal Basin is separated from the better studied Chihuahua Basin by a ridge of Precambrian through Permian rocks that runs from the Precambrian and Permian outcrops of Sierra del Cuervo, north of Aldama, north under the weakly deformed platform carbonates of Sierra Peña Blanca (Fig. 4.10.). The revised isopach of the basal Cretaceous Las Vigas Formation highlights an apparent ridge continuing the basement of Sierra del Cuervo all the way north to the Burro Florida uplifts of southwestern New Mexico (Fig.4.12). The interpreted Permian exposures at Sierra Alcaparra and Sierra Samalayuca both plot along the east side of this proposed basement ridge as it continues north-northwest to the southwest side of Sierra Samalayuca and continues northwest to the Burro-Florida Mountain basement outcrops of southwest New Mexico. They appear to be inverted basement blocks uplifted against the basement ridge along the west side of the Chihuahua Basin (Fig. 4.71). This interpretation is consistent with the west-directed thrusting documented along the west margin of the Chihuahua Basin (Hennings, 1994).

The name Casas Grandes Platform was chosen from the most prominent location on the, now known to be separate, platform west of Sierra Santa Lucia that was formally included with the Aldama Platform Ridge. Mapping of thrusting by the author at Sierra Santa Lucia, Sierra Banco Lucero, Sierra Mojina, Rio Tinto (Terrasas), Salamex (Cuauhtémoc) and Descubridora (Fig. 4.71) demonstrate the presence of a significant shortening of a major basin situated between the basement exposure at Sierra del Cuervo (north of Aldama) and undeformed Aurora Limestone of Sierra Peña Blanca invalidating the Aldama name as applied to the basement platform to the west. Folded Late Cretaceous strata at San Pedro Corralitos 42km NE and at 62km NE of Nuevas Casas Grandes suggests another possible northwest-trending branch of the Carrizal Basin connecting it to the Bisbee Basin. No other evidence was observed in the field or in imagery that any other basins subdivide Nuevo Casas Grandes Platform was observed. Because of volcanic cover it cannot be said with certainty that no other basins disrupt the provisionally named Casas Grandes Platform.

One observation of possible use in structural mapping is that all of the inverted basement blocks mapped in this study (Sierra Santa Lucia, Sierra Mojina, Sierra Samalayuca and possibly Sierra Alcaparra all in Chihuahua and Sierra Atotonilco and Sierra Ramirez in Durango) occur along the west margin of the shortened basin (Fig. 4.10.2). In the case of northern Mexico this is the side toward the eastern Pacific subduction zone. Several possible causes of this distribution include asymmetry produced during development of the extensional basin by a delamination model (Lister and others, 1986) or asymmetry produced in an originally symmetrical pure shear extensional basin by the sequential effect of the western basement platform (in the Mexican model) being forced into the extensional basin where the basin margin listric faults under ride the adjacent extended basement blocks initially forcing them upward while the less ridged basin filling strata is subsequently pushed out-of-the-basin onto the adjacent platform. Because the basin was filled following extension it is difficult to determine if either case is correct or the asymmetry is the product of both mechanisms. Access to deep reflection seismic data or modeling might help resolve this question.

Most discussion on the distribution of metal deposits in Mexico have focused on possible relationships with magma variation chemically and temporally (Clark and others, 1982). Additional focus has been on the possible relationship of ore deposits and basins (Megaw, 1988; Lyons, 2008).The model that was driving the work done for this study was that of the relation of mineralization to the intracratonic basins, particularly their structural margins. While one successful discovery was made at Cinco de Mayo (Sierra Santa Lucia), Chihuahua utilizing this model, it was demonstrated that many other known deposits, Mapimi, Naica, and Sierra Ramirez as some examples, show a strong spatial correlation with the structurally complex basin margins.

CONCLUSIONS: CARRIZAL-MEXICAN INTRACRATONIC BASINS

The Carrizal Basin is proposed as an intracratonic extensional basin that developed during the Late Triassic through Middle Jurassic contemporaneously with the Chihuahua extensional basin (trough) in central Chihuahua. The two basins, previously discussed as one basin (Haenggi, 2002) are separated by a structural ridge. This ridge continues southeast from the Burro and Florida Mountains of southwest New Mexico, bends more southerly north of Villa Ahumada and then continues under Sierra Peña Blanca south to Sierra del Cuervo where it crops out again. Drilling, published measured sections, outcrops and the revised contour map of the Las Vigas Formation originally compiled by Haenggi (2002) support the existence of this ridge called here the Florida-Aldama Ridge.

Bidirectional thrusting and folding between the Florida-Aldama Ridge and the stable platform documented west of Sierra Santa Lucia defines a new separate basin the Carrizal Basin. Tectonic shortening of the originally extended crust under the various intracratonic basins creates a space problem for the basin fill deposits that are folded and thrust out of the of the basins on to the adjacent platforms. The folding and thrusting is bidirectional but elements of the tectonic shortening are not completely symmetrical. Thrusting along the southwest margins of the basins tend to be stacked as observed at Sierra Santa Lucia, Chihuahua and Sierra Ramirez, Durango, whereas along the northeast margins of the basins thrust ramps onto the platforms such as the Chihuahua Basin and the west and south sides of the Coahuila Platform

In the intracratonic basins all inverted basement blocks documented or observed in this study (Samalayuca, Sierra Santa Lucia and Sierra Mojina, in Chihuahua and Atotnilco and Sierra Ramirez in Durango) occur along the side of the basin closest to the zone of subduction. This asymmetry may have developed during the extension (delamination as opposed to pure shear) or be an asymmetry resulting from the compressive forces building sequentially through time across the basins affecting the southwest sides of the basins first and the northeast side of the basins last. Steeper faulting on the subduction side of the basin could produce inverted basement blocks during shortening while lower angle ramp faults that thrust on to the adjacent platform during shortening. An alternative is that, whether the extension was asymmetrical or not, the rigid western sides of the basins are being pushed under the basin fill and extended basement resulting in the inverted basement blocks on the west margin, while shortening of the basin fill pushes it over the eastern margins without uplifting the extended basement floor of the basin.

The term Aldama Platform has been used to describe a proposed platform projecting west of Aldama, Chihuahua. A mostly covered belt of bidirectional folded and thrusted Lower Cretaceous limestones crops out south of the better exposed Carrizal Basin at Terrazas (Rio Tinto), Cuauhtémoc (Salemex), and Descubridora north of Chihuahua City. This belt of shortened basin strata separates the basement of the Aldama region from the platform to the west and necessitates a new platform name here designated the Casas Grandes Platform.

Past studies use of facies and thicknesses to delineate the intracratonic basins of northern Mexico was perfectly adequate in light of the then current geosynclinal theories of down warps and troughs. This study builds on those earlier stratigraphic studies, by adding structural mapping that confirms the theory of basin inversion of former extensional basins as the primary mechanism of development of the northern branches of the Sierra Madre Occidental fold belts, the Carrizal, the Mexican, the Chihuahua and the Sabinas Basins and allows more precise delineation of the structural boundaries of the basins and creates a stronger foundation for understanding the tectonic history of the region. Mapping the direct effects of structural shortening such as bidirectional thrust and fault-bend folds of supracrustal strata and inverted basement blocks proves very useful to more precisely delineate the paleo-basins.

Documenting the association of major Ag-Pb-Zn replacement deposits with the complex structural development along the basin margins by shortening induced basin inversion gives greater credence to the long discussed model of carbonate replacement deposits associated with the intracratonic basin margins of Mexico (Fig.4.72). The Cinco de Mayo District in Sierra Santa Lucia, Chihuahua was discovered in 2008 on the west margin of the newly defined Carrizal Basin as a direct field application of this model. The Sierra Ramirez, Durango mineral districts of Acasio and Pavo (Fig. 4.72) were explored for further mineral potential. South-directed thrusting over an inverted basement block of Nazas tuffs indicates the same style of basin inversion along the southern structural margin of the transverse portion of the Mexican Basin. Mapping at both Sierra Santa Lucia and Sierra Ramirez confirm a mineral district association with complex out-of-the-basin thrusting involving inverted basement blocks along the subduction facing side of the basins. Mapping at the Mapimi and Pavo, Durango metal districts (Fig.4.72) both document the opposing out-of-the-basin thrusting to the East away from the subduction zone. In these four cases the bidirectional out-of-the-basin thrusting provides an environment favorable for the emplacement of magmatic thermal engines and a plumbing system through which the heated fluids can flow. Another inverted basement block of Nazas is documented at San Fermin, Durango (Fig. 72) on the west side of the Mexican Basin.

The age of the basin shortening can now be more accurately dated as occurring from the late Cenomanian through the Middle Eocene. Initiation of thrusting and uplift has been documented in PEMEX exploration drill hole Parral-1 (Fig. 4.1) with Upper Jurassic and Lower Cretaceous strata from the Mezcalera Marginal Basin being thrust onto the Lower Cretaceous carbonate platform as described in Chapter 3. Also at Salamandra, Durango it is further documented by debris flows of limestone detritus from uplifted Albian-Aptian carbonate platforms on the Durango Inverted Basement Block (as discussed in Chapter 3) being deposited within the Late Cenomanian-Turonian Indidura Formation. A new date on a folded Middle Eocene rhyolite flow at Division del Norte, Chihuahua (sample JLDDN-01, see Appendix A) documents that east-directed thrusting out of the Mexican Basin on to the Coahuila Platform continued at least through the Middle Eocene.

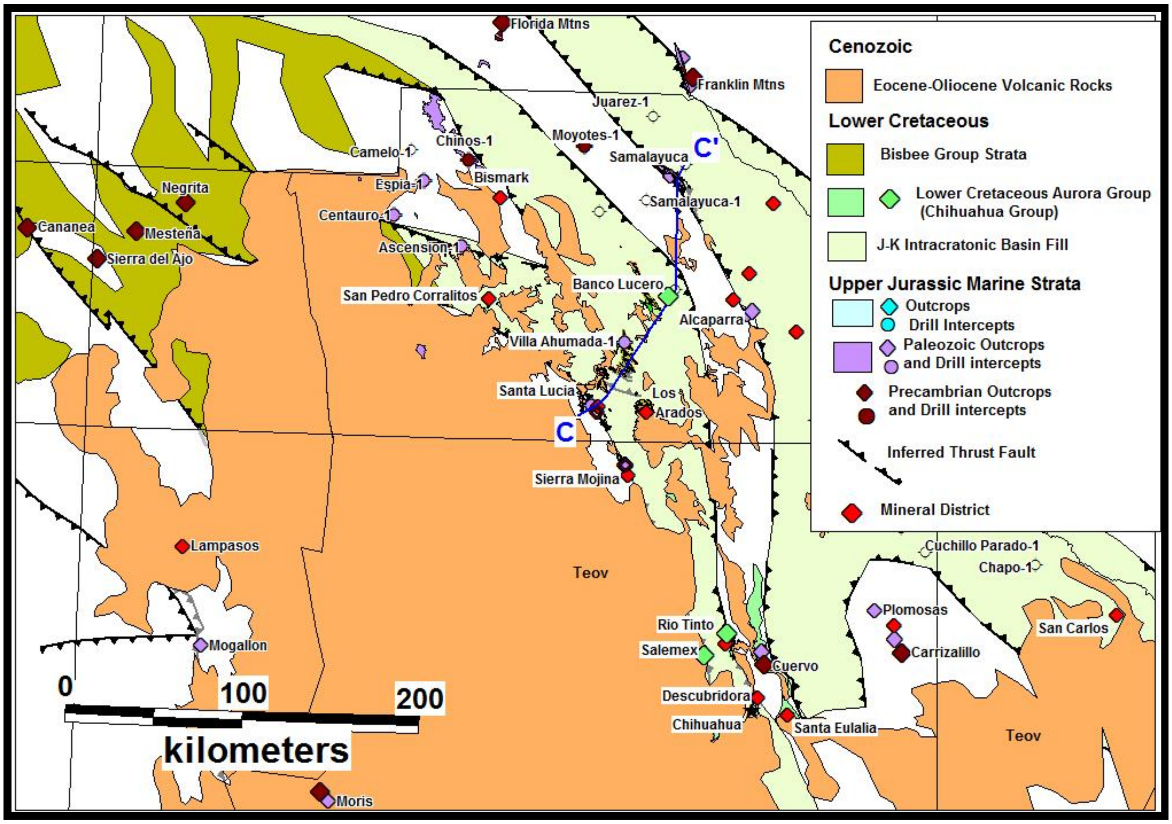


Figure 4.1 Location of important outcrops and mapping projects that have led to the newly interpreted Carrizal Basin to the west of the Chihuahua Basin.

Figure shows the regional setting of the study for this chapter, locations mentioned in text including Precambrian and Paleozoic outcrops and PEMEX intersects, Ag-Pb-Zn mineral systems, and PEMEX drill holes not reaching Paleozoic or older units (open circles). Cross section C-C' projects from Sierra Santa Lucia to Sierra Samalayuca. The continuous black structures are observed and broken black structures are inferred. The direction of thrusting (teeth on upper plate) determined from direction indicated by fault bend folds and fault propagation folds particularly when thrust upon flat lying platform strata.

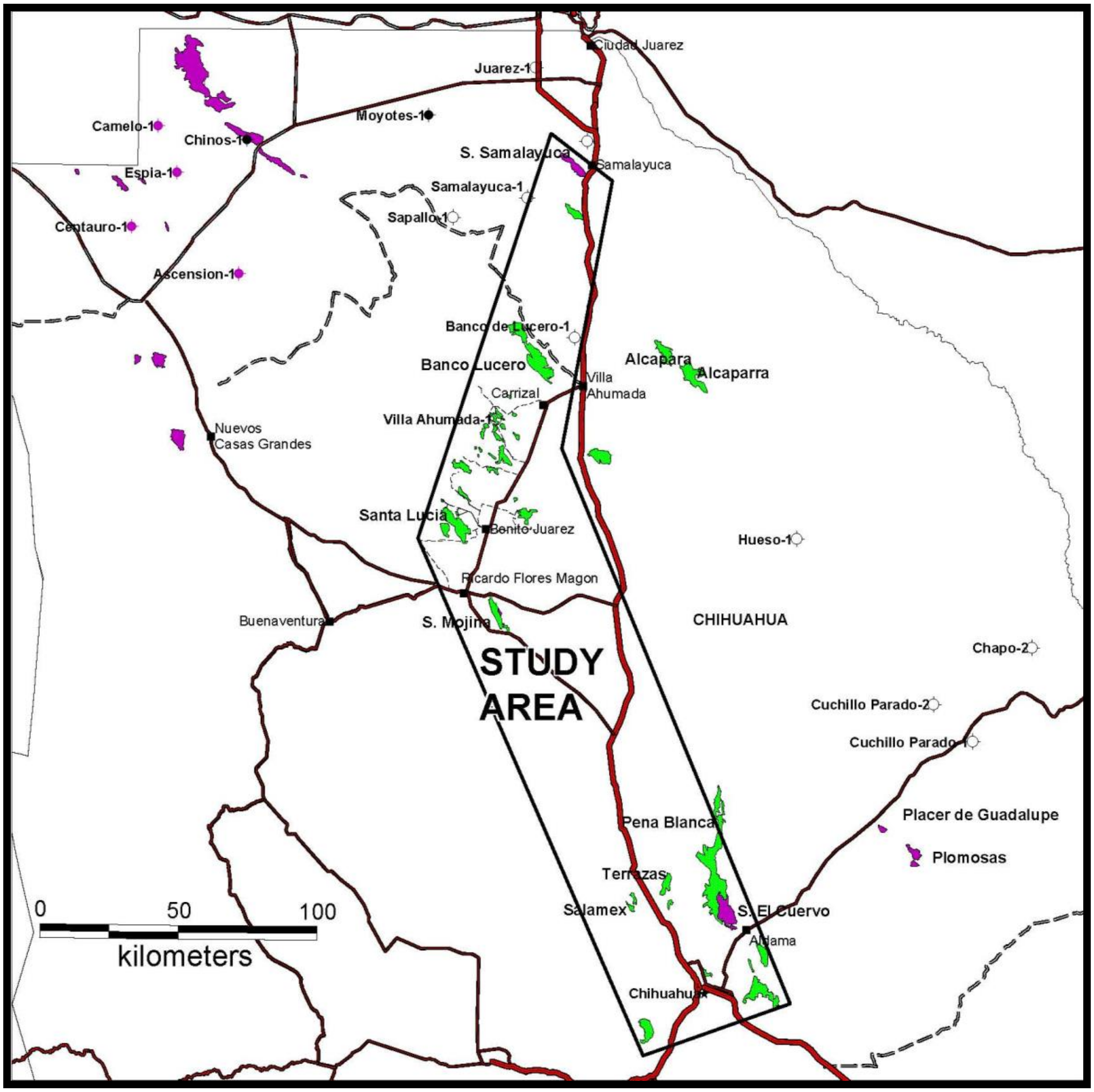


Figure 4.2 Lower Cretaceous strata (green) studied or discussed as a part of this study in north central Chihuahua.

All known outcrops of Paleozoic strata in the area are shown in purple. Additional mapping that aides in projecting the Carrizal Basin into the Chihuahua City area also shown.

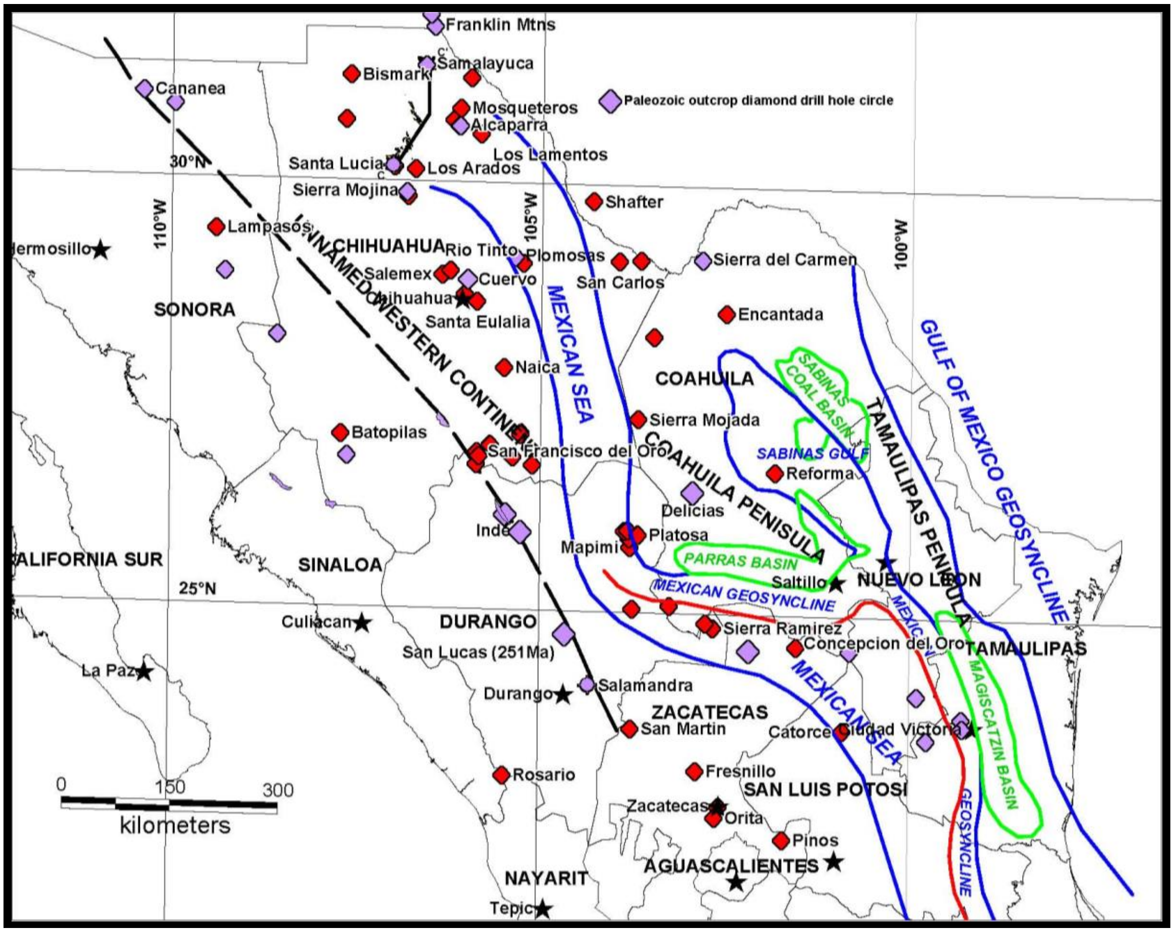


Figure 4.3 Jurassic basins controlling the facies and thicknesses of Lower Cretaceous strata based on 76 measured sections from Humphrey and Díaz, 2003 after Humphrey, 1956.

Purple diamonds indicate known and interpreted Paleozoic occurrences and purple circle with spikes at Santa Lucia, Chi. and Salamandra, Dgo. are two interpreted Paleozoic occurrences in drill core encountered during this study. The red diamonds are Ag-Pb-Zn mineral systems that show only moderate correlation with these proposed basins.

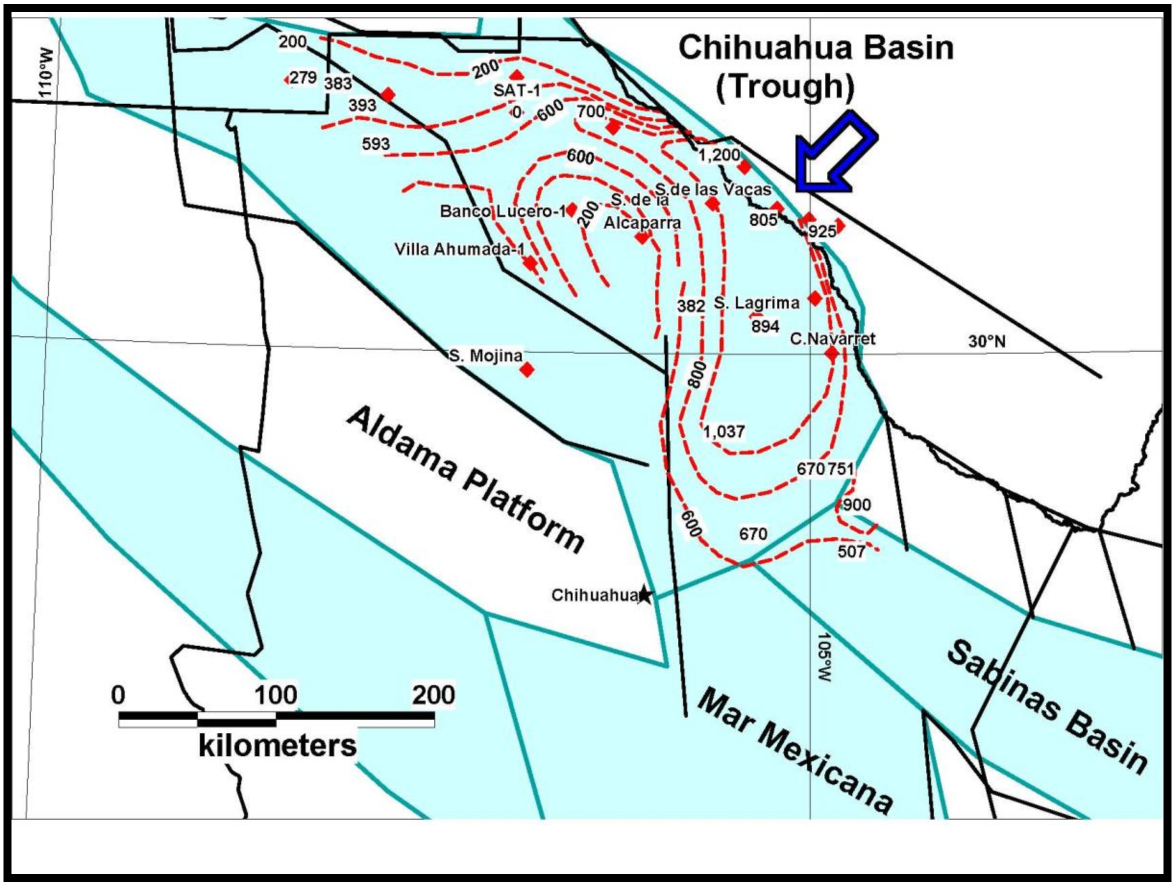


Figure 4.4 Structural model of the Chihuahua Basin (trough) from Haenggi and Muehlberger, 2005).

Red isopach lines indicate Las Vigas Formation thickness interpreted by Haenggi (2002) from measured sections and exploration drill data.

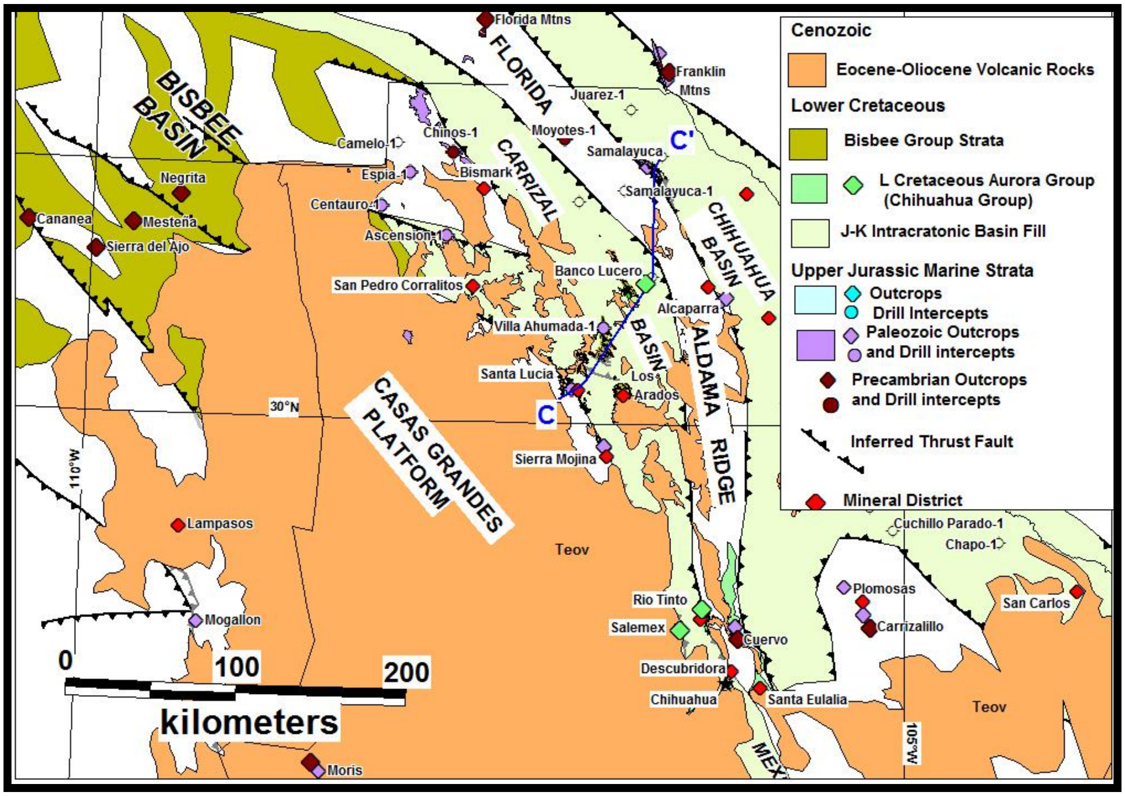


Figure 4.5 Regional setting of the newly proposed extensional basin west of the Chihuahua Basin with the Sierra Madre Volcanic Province cover.

Cross section line C-C' (in dark blue) is a new section based on new surface reconnaissance mapping from Samalayuca to Sierra Santa Lucia. Despite extensive volcanic and alluvial cover mapping at Salamex, Rio Tinto (Terrazas), Descubridora and Sierra Peña Blanca east of Rio Tinto documents bi-vergent thrusting. This supports the proposal that the newly proposed Carrizal Basin projects into the Chihuahua City area. Studies of the Mexican Basin to the south of Chihuahua City area indicate continuity between the Carrizal and Mexican Basins.

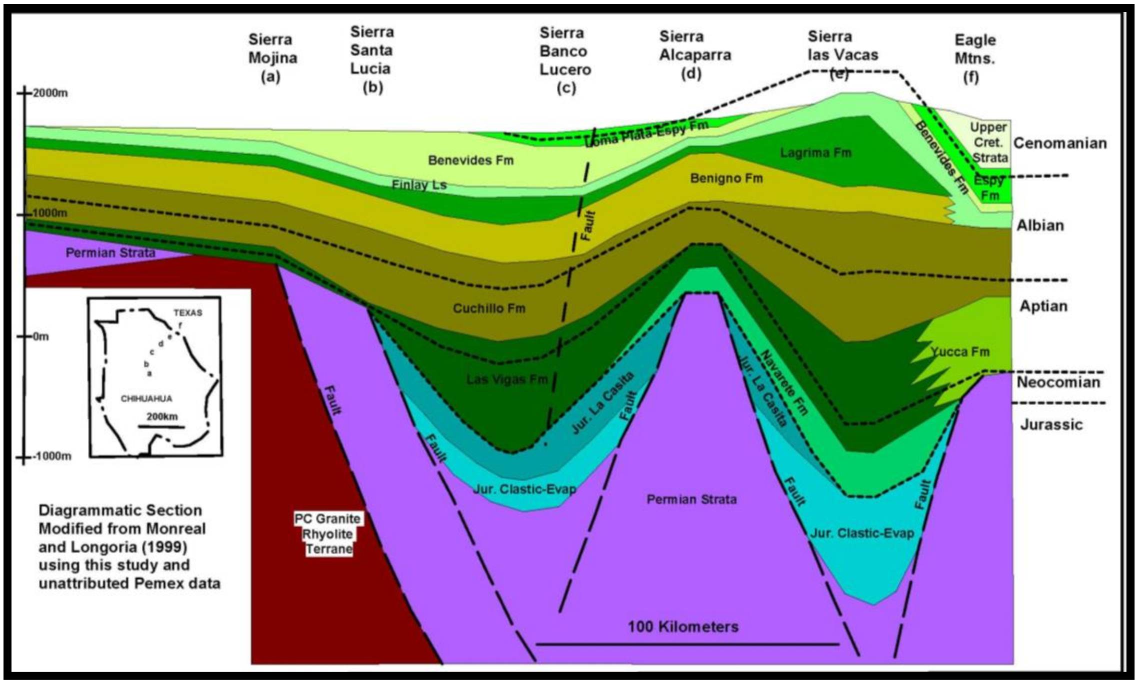


Figure 4.6 Diagrammatic lithologic correlation diagram of Monreal and Longoria (1999) for the Chihuahua Basin can now be continued across the Carrizal Basin south Sierra Banco de Lucero of their section.

Diagram now includes a revision of Sierra Banco de Lucero stratigraphy from mapping of the range for this study, mapping from Sierra Santa Lucia and Sierra Mojina and intervening reconnaissance mapping. It also includes observations from an unattributed PEMEX cross section and brief references to Paleozoic intercepts in PEMEX well Villa Ahumada-1.

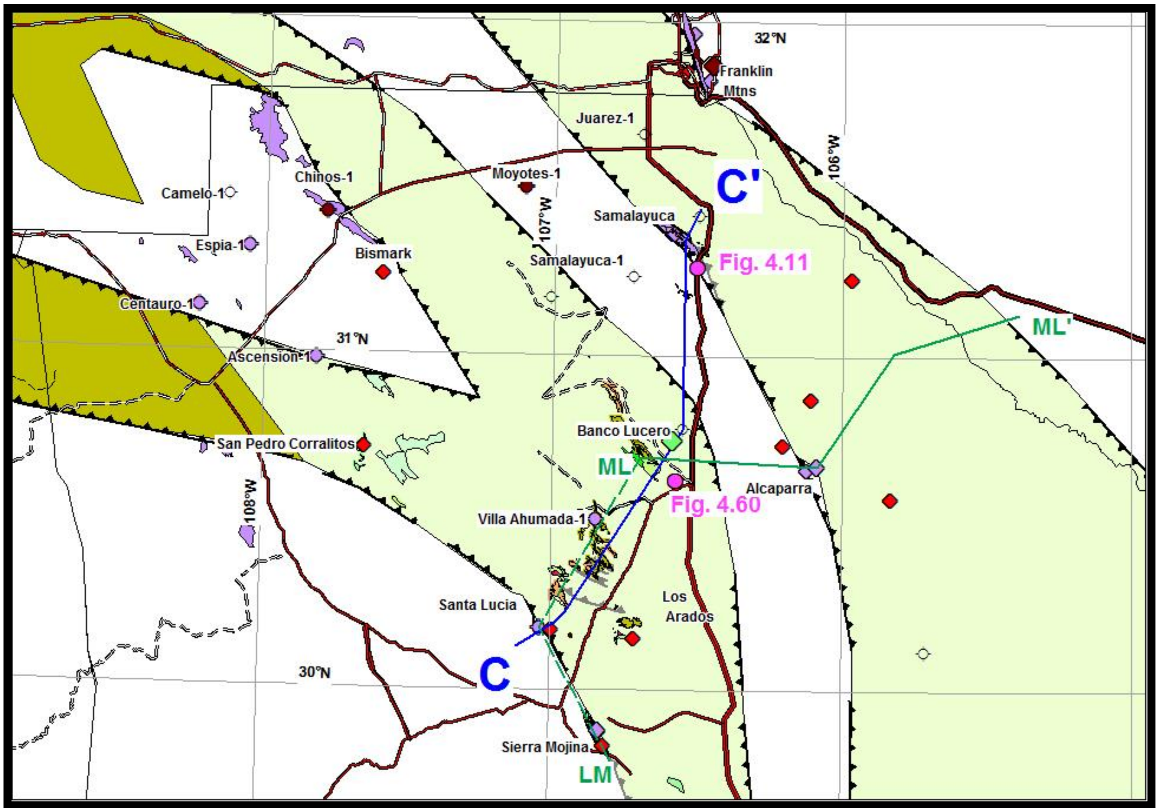


Figure 4.7 Location map of the expanded lithostratigraphic chart of Monreal and Longoria (1999).

Section ML-ML' is section of Monreal and Longoria (1999). LM to ML is extension of their section. Blue line of section C-C' is new section on FIG. 4.6. Pink locations are field photo locations. Map includes drill holes and outcrops that contribute to defining the geometry of the northern Mexico intracratonic basins and their margins.

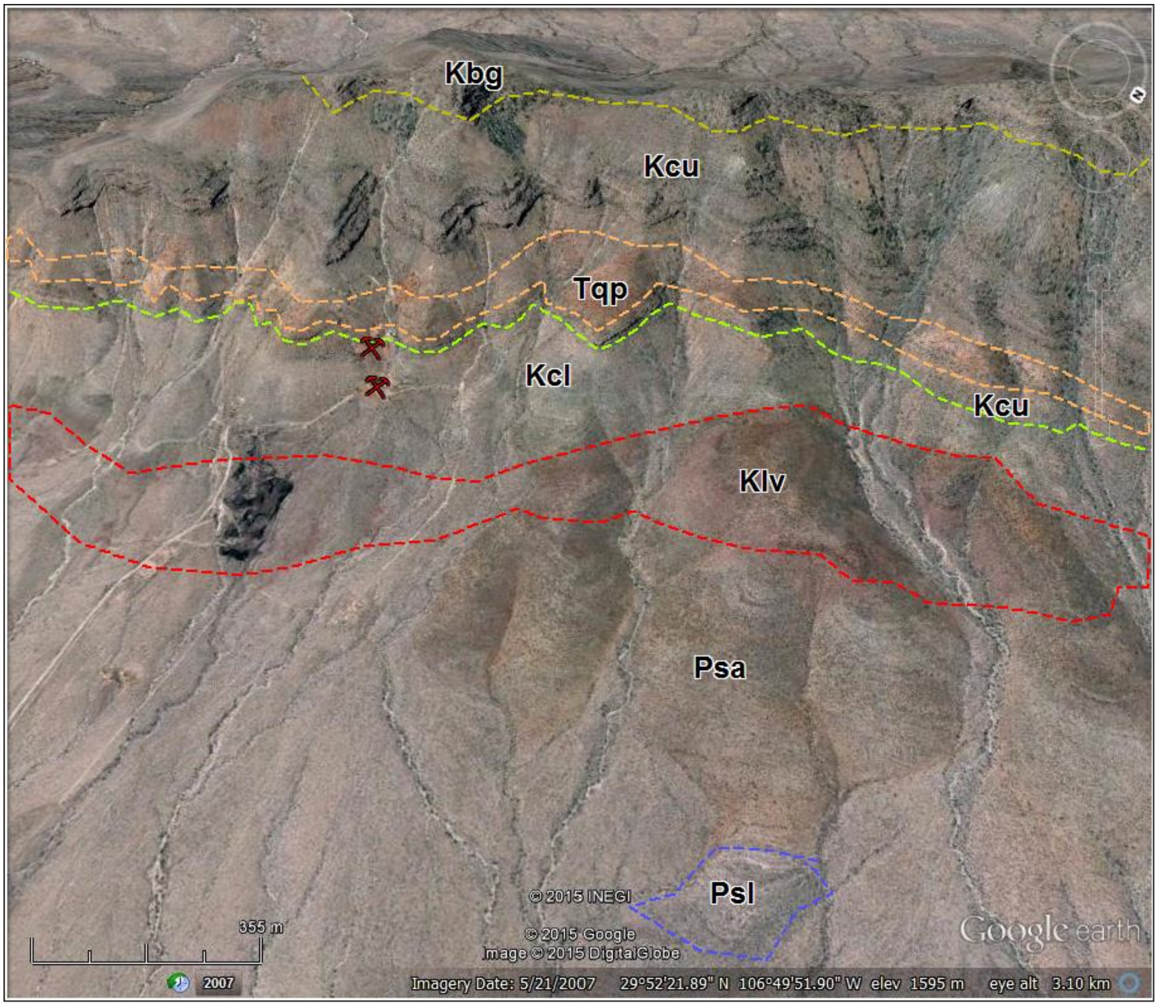


Figure 4.8 The east face of Sierra Mojina exposes a Permian through Lower Cretaceous Middle Albian Benigno Formation.

The shown formations include; Psl-Permian Scherrer Limestone; Psa- Permian Scherrer arkose; Klv- Lower Cretaceous Las Vigas Formation; Kcl- Cretaceous Lower Cuchillo; Kcu- Upper Cuchillo with Tqp- an altered Tertiary quartz porphyry sill intruded in the lower part; and Kbg- Cretaceous Benigno Formation capping the ridge. The dark patch within the Las Vigas is an old mill site and the mines are a lower adit and upper workings of the Caracoles Mine.

Figure 4.9 Outcrop of propylitically altered Permian Scherrer arkosic mudstone on east face of Sierra Mojina.

Propylitized presumed Permian Scherrer Formation with pink peidmontite and green epidote clots. Coarse calcite and sparse wollastonite sometimes observed in cores of epidote clots.

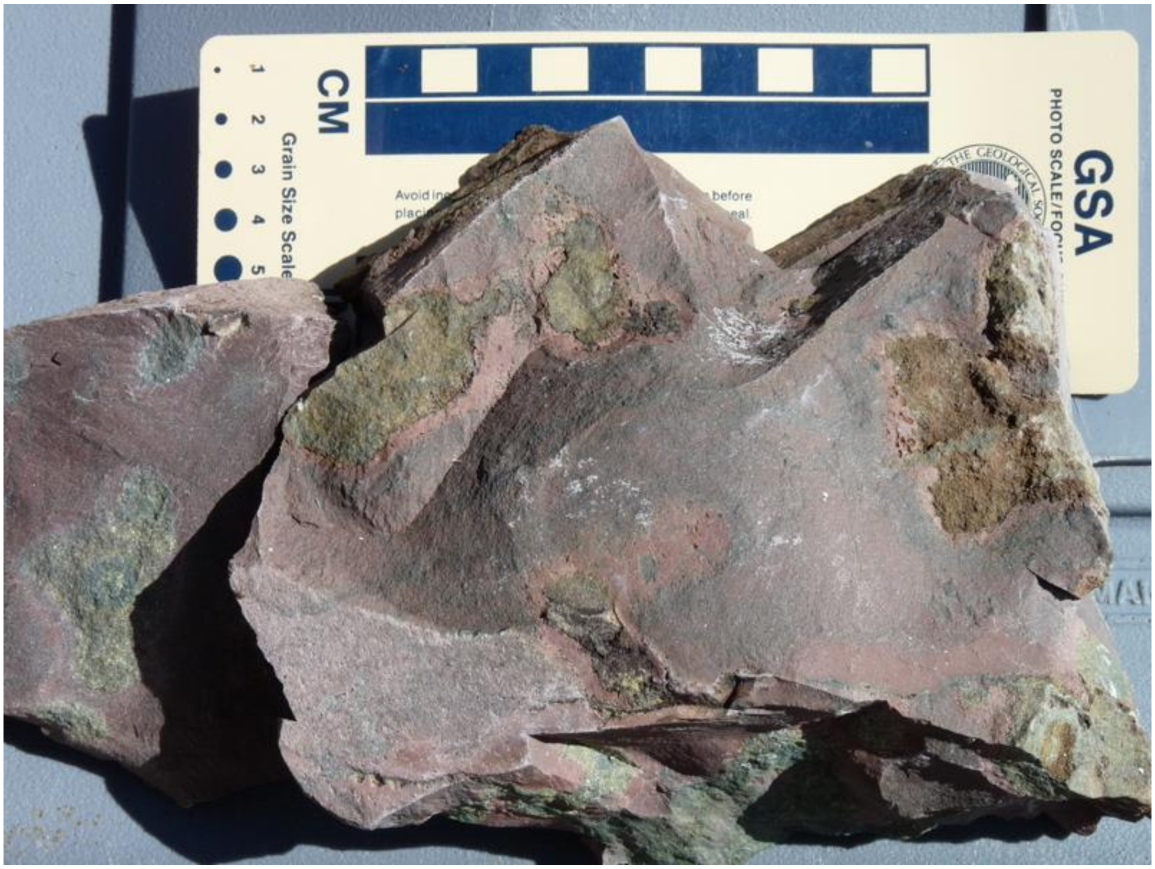


Figure 4.10 Close up of assumed Permian muddy arkose with epidote clots after pedogenic caliche nodules with piedmontite in groundmass.

Characteristic of Scherrer arkose (Tim Lawton, personal communication).

Figure 4.11 Folded Permian sandstone and conglomerate looking north to the southwest flank of Sierra Samalayuca.

Southwest inclined fold axis (Berg, 1980) exposed in an inverted basement block along west edge of Chihuahua Basin. Photo location indicated on Fig. 4.7.

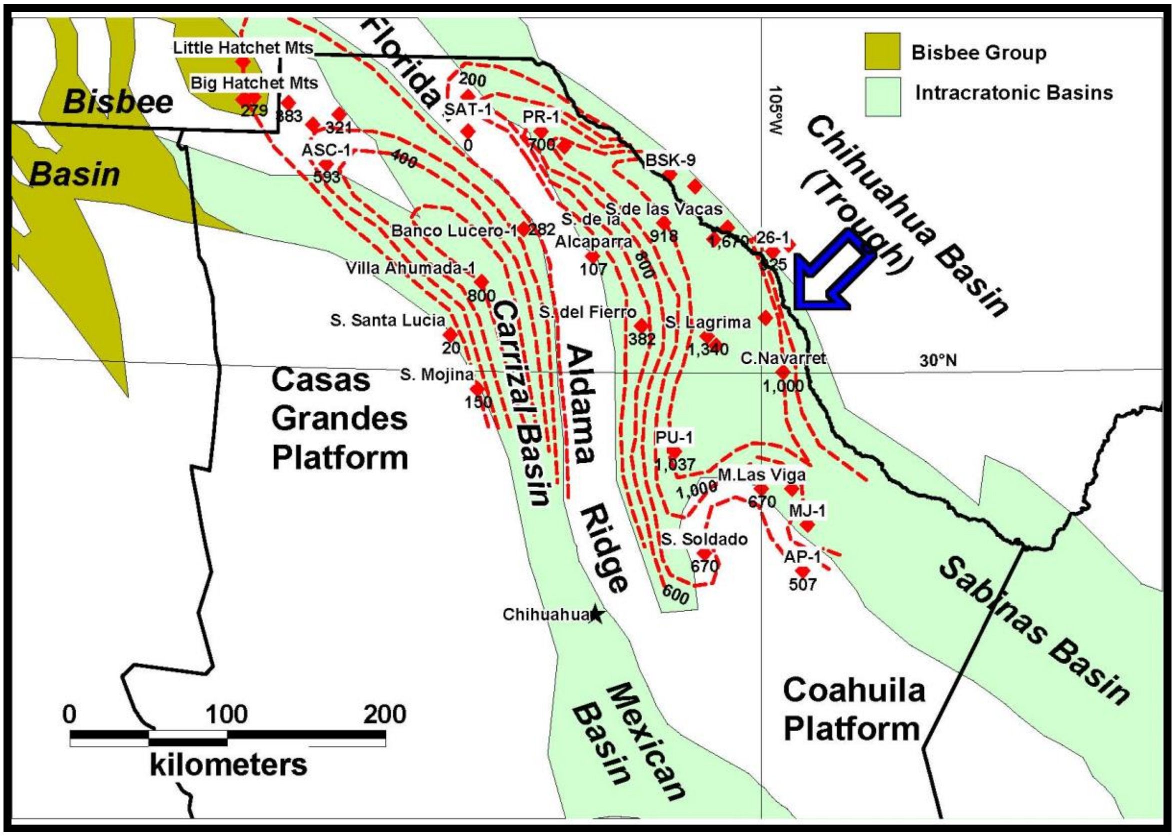


Figure 4.12 Thickness contour map of Las Vigas Formation modified from Haenggi (2002) highlights the ridge separating the Carrizal and Chihuahua basins.

Map modified from Haenggi (2002) shown in Fig. 4.4, with new thickness data points from this study along with observed minimal structural deformation compared to the basin strata, both taken as evidence of a basement ridge separating the Chihuahua Basin from the Carrizal Basin. There is a suggestion of this ridge on Haenggi's map (Fig. 4.4) but he chose to assume PEMEX's logging of zero meters of Las Vigas in SAT-1 (near the north end of this proposed ridge) to be a misinterpretation.

Figure 4.13 Schist-bearing conglomerate from Las Vigas Formation on east face of Sierra Mojina.

Figure 4.14 Close up of sample JL-MJ-01 of Las Vigas Formation near base of east side of Sierra Mojina dated by whole rock U-Pb on detrital zircons.

Photo shows schist and quartz vein fragments that make up the majority of clast (sample JL-MJ-01, see text, Appendix A and Supplemental Data for analytical data).

Figure 4.15 Close up of Las Vigas at Sierra Mojina at the base of the east slope showing rhyolite clast in conglomerate .

Figure 4.16 Bleached dolomitic limestone and solution breccias of Lower Cuchillo sabkha deposits from the west side of Sierra Santa Lucia.

Solution breccias formed during subaerial exposure of evaporitic strata in the Lower Cuchillo. Core is 6.3 cm diameter and from CM09-123 on the west side of Sierra Santa Lucia (see Fig.4.40c for hole location).

Figure 4.17 Bleached stromatolitic sabkha beds associated with evaporitic lagoonal facies of Lower Cuchillo.

Core (6.3 cm diameter) from drill hole CM09-123 on west side of Sierra Santa Lucia (location shown on Fig. 4.40c).

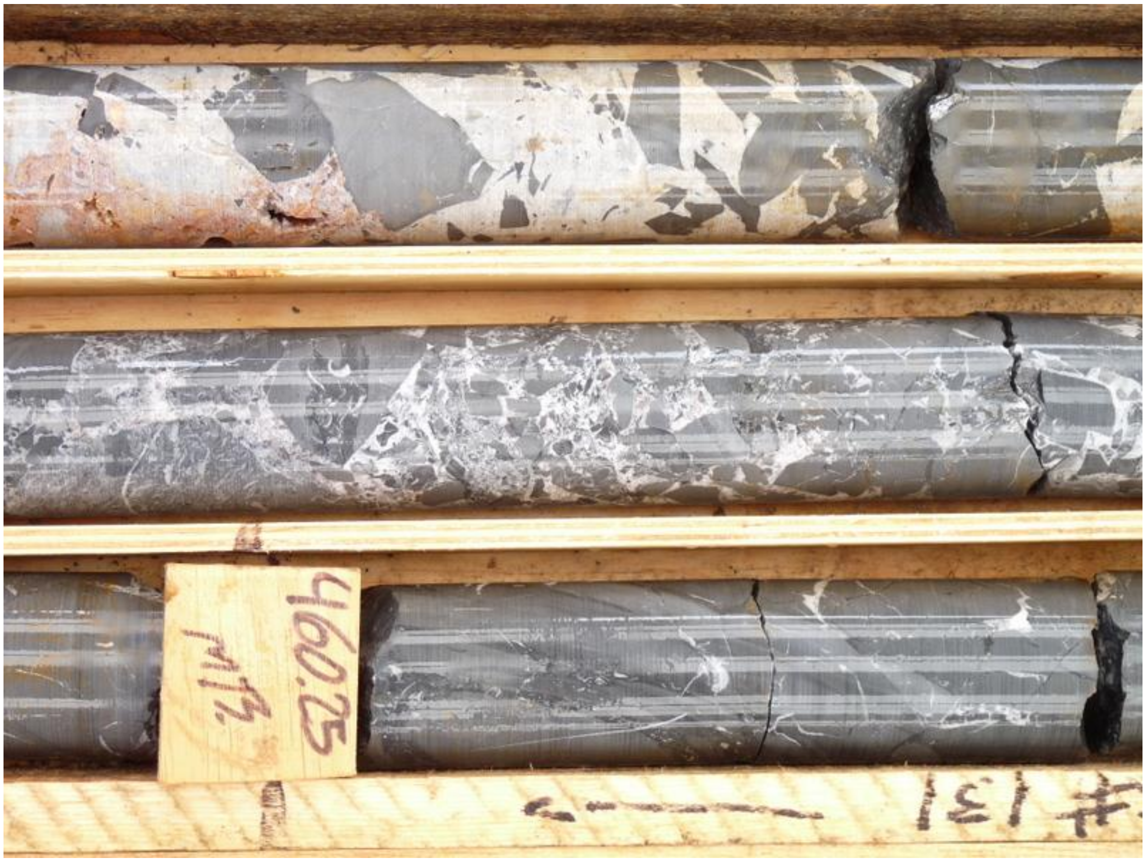


Figure 4.18 Collapse breccias developed above sabkha evaporites when they were dissolved during periods of subaerial exposure.

The common hematite staining in otherwise unoxidized rock is evidence of this early exposure. Down is to the left in this core from CM09-123 (location shown on Fig. 4.40c).

Figure 4.19 Fossil rich lagoonal patch reefs with mud matrix at 411.5 m depth in CM09-123 (up is to the right and location shown on Fig. 4.40c).

Figure 4.20 Upper Cuchillo Limestone Member on west face of southeast ridge of Sierra Santa Lucia.

Upper member consists of 1 to 2 m bedded limestone with shale partings. Massive limestone capping ridge is a reef of the Benigno Formation.

Figure 4.21 Upper Cuchillo Member along east face of Sierra Mojina.

Massive spire to north is part of Benigno Formation reefs capping Upper Cuchillo.

Figure 4.22 Most complete Lower Cretaceous section known in the Carrizal Basin is exposed over Permian Scherrer Formation in Sierra Mojina.

Scherrer limestone (Psl) and Scherrer arkose (Psa) make up the exposed inverted basement. Las Vigas Formation (Klv) and Lower and Upper Cuchillo (Kcl, Kcu) make up the pre-Aurora Group Lower Cretaceous at Sierra Mojina. The Upper Cuchillo hosts local mineralization along the upper and lower contacts of a distinctive argillized quartz porphyry sill (Tqp). Although the complete Aurora Group is exposed in the range only the Benigno Formation is exposed in this image. Inclined Google Earth image looking down and to the west.

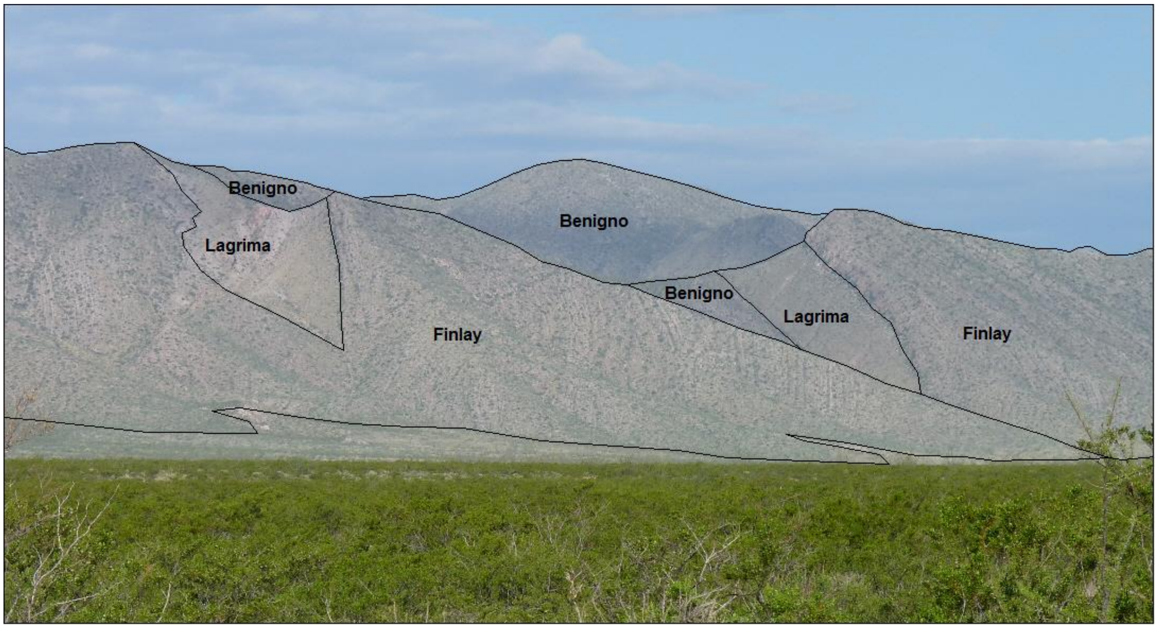


Figure 4.23 Outcrops of the lower Aurora Group as seen in the northern part of Sierra Santa Lucia.

The marl of the Lagrima forms grass-covered slopes, the limestones of the Finlay and Benigno form sparse brush-covered outcrops (photo taken from north end of Cerro Cinco de Mayo).

Figure 4.24 Core from 573 m depth in drill hole CM09-110 of typical fossil and chert-rich reefal facies of the Benigno Formation.

Rudists dominate the fossil assemblage with scattered pectins and oysters. The reefal facies is lithologically indistinguishable from the Finlay Formation. Down hole is to the top and left (location shown on Fig. 4.40c).

Figure 4.25 Outcrop photo from the crest of Cerro Ruso of the bioturbated top of the Benigno, the most distinctive feature of the formation.

The bioturbated top ranges from one to ten meters thick. In the field it is the first thick limestone bed at the base of the Lagrima.

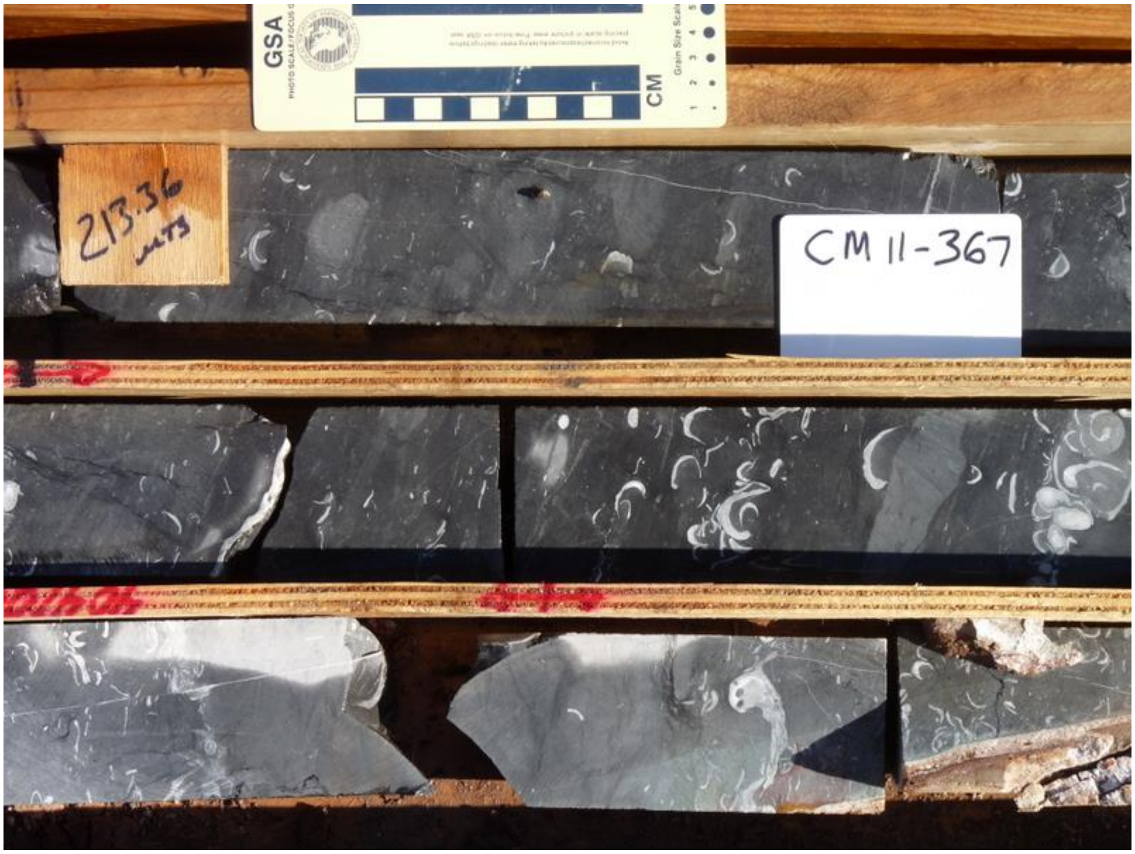


Figure 4.26 Normal appearance of Lagrima fossiliferous marl in drill core (CM11-367). Down is on the top and left corner of core (location shown on Fig. 4.40c).

Figure 4.27 Outcrop photo of the fossilierous Finlay from northeastern Sierra Santa Lucia with prominent silicified rudist fossils.

Figure 4.28 Flat platy storm rip up clasts found from below the solution cavity horizon 10 to 20 m below the top of the Finlay at 583.2 m in drill hole CM09-122.

Down is to the right (location shown on Fig. 4.40c).

Figure 4.29 This broader view illustrates the relation of the solution cavity to the underlying storm clast horizon.

Because of the high permeability of the storm layers, normally only the resulting solution cavity is observed. Down is to the right and down (location shown on Fig. 4.40c).

Figure 4.30 Core of the black finely laminated calcareous shale that is typical of the majority of the Benevides Formation in the Carrizal Basin.

Core (6.3 cm diameter) from drill hole CM11-378 (location shown on Fig. 4.40c)

Figure 4.31 Drill core from CM11-378 showing transition from dominate black calcareous shale to less common gray micritic limestone.

Down hole is to the top left (location shown on Fig. 4.40c).
Top is bottom right corner and bottom is upper left corner.

c

Figure 4.32 Benevides Formation includes sparse pelecypods similar to those that are more abundant in the Lagrima.

Arrows to the left on core boxes indicate down hole direction (location shown on Fig. 4.40c).

Figure 4.33 Laminated sand (first quartz sand above Las Vigas) and shale of the Indidura Formation.

Laminae are cut by a small scale fault-bend fold. Up is to the left.

Figure 4.34 Typical variations seen in the Ojinaga Formation (from drill hole CM371).

Variations include red to greenish-gray mudstones (272m), red mudstone to greenish-gray sandstone (477m), and greenish-gray sandstone with mudstone clasts. Down hole is to the left and top (location shown on Fig. 4.40c).

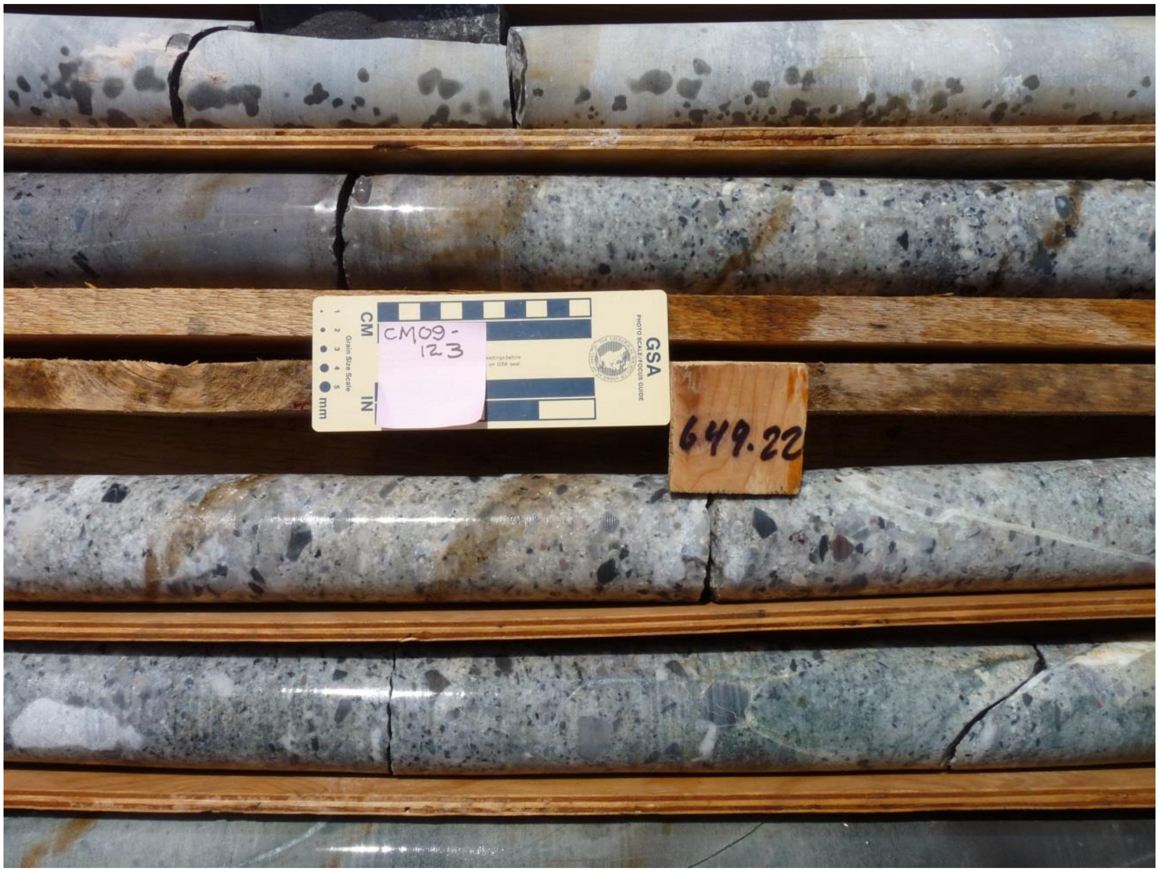


Figure 4.35 Conglomeritic facies from Ojinaga in CM09-

Figure 4.36 Coarse sandstone found in Cenomanian Ojinaga Formation of CM09-124 at 185.93m depth.

Sandstone consists of quartz and volcanic rock fragments (location shown on Fig. 4.40c)

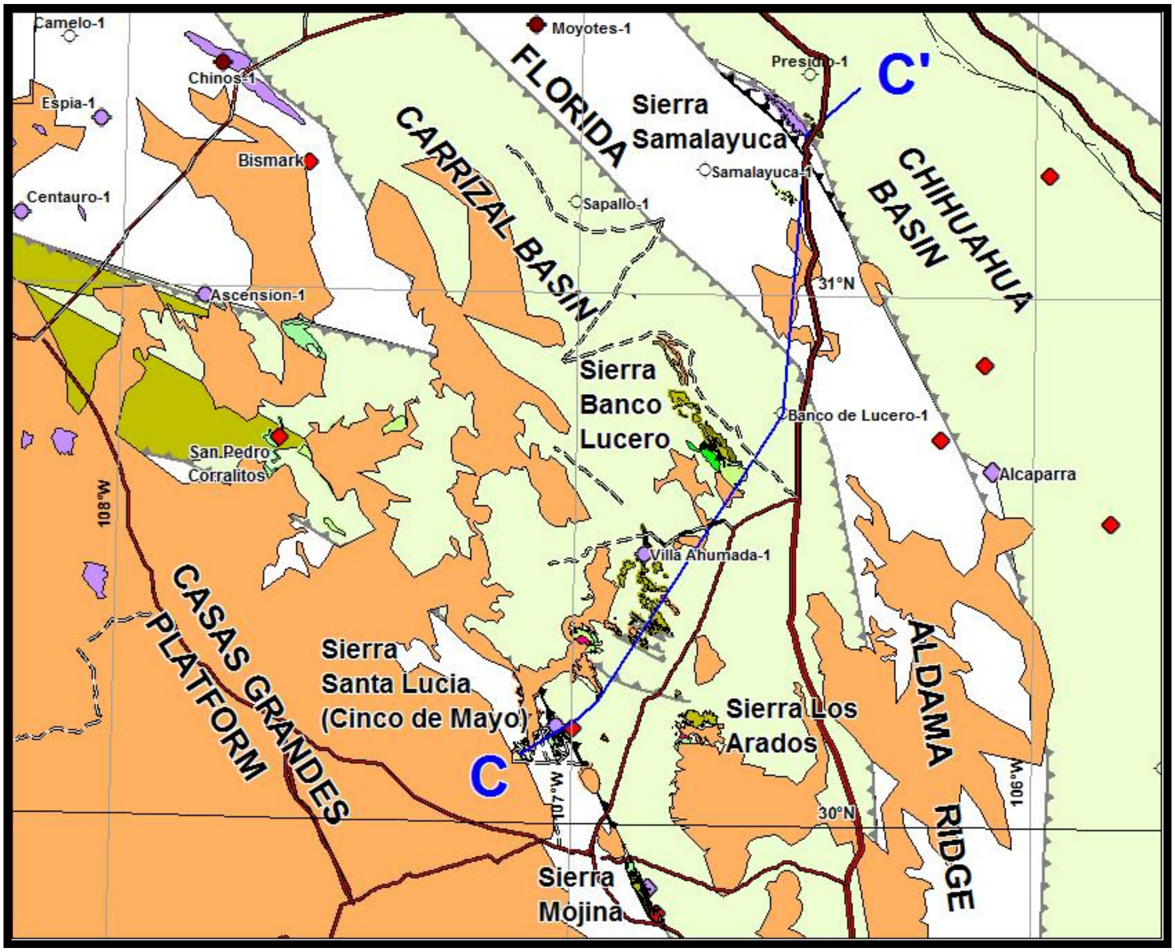


Figure 4.37 Map showing the location of and access routes to Sierra Mojina, Sierra Santa Lucia, Sierra Banco de Lucero, and Sierra Samalayuca.

Cross section C-C' crosses the Florida-Aldama structural ridge from Sierra Samalayuca and the Carrizal Basin to the Casas Grandes Platform. Pale green represents the interpreted Late Triassic-Jurassic basins transecting the Mexican craton.

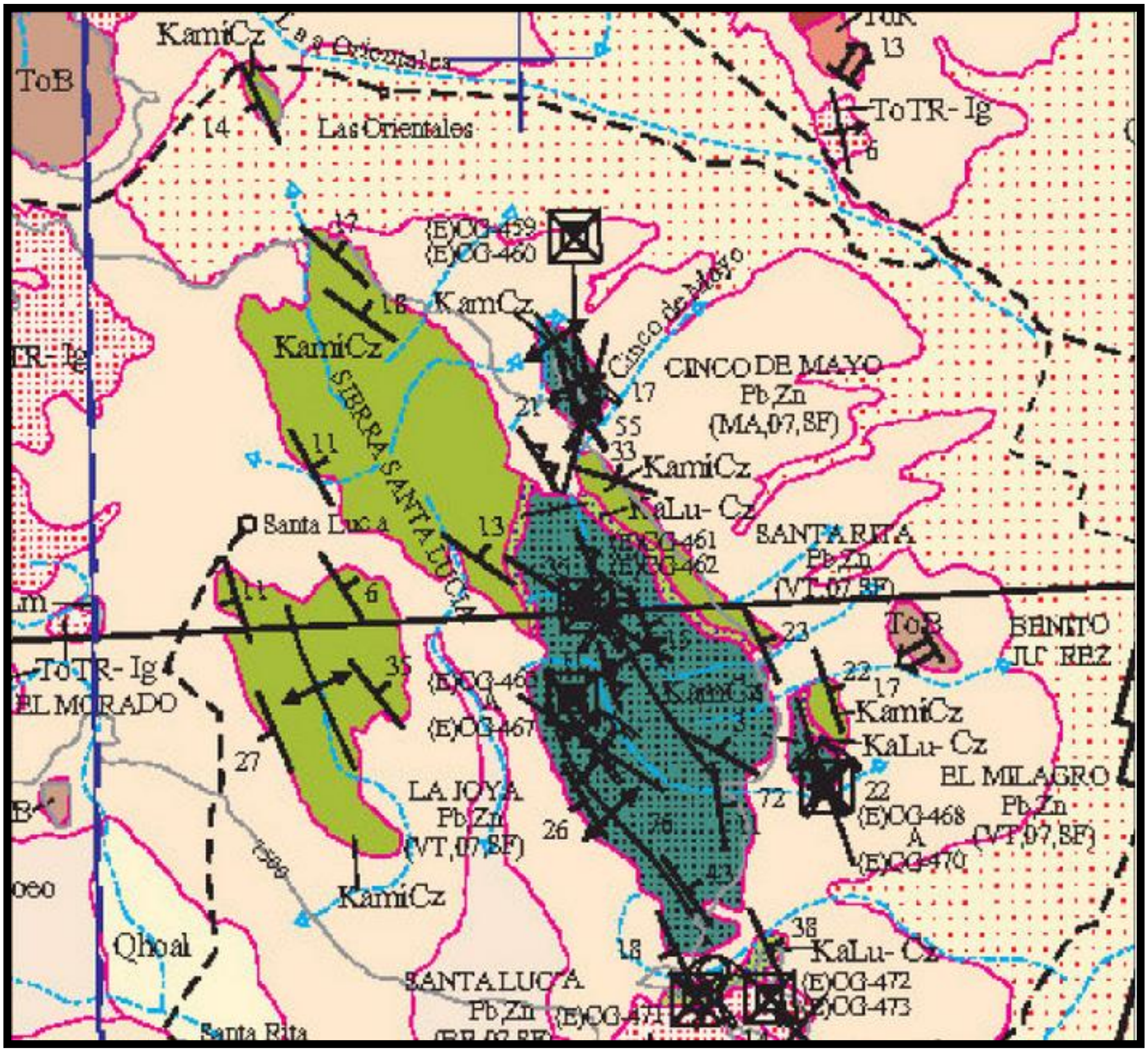


Figure 4.38 Published map (Hernandez-Velazquez and others,2002) of Sierra Santa Lucia uses Texas nomenclature.

KamiCz is the Glen Rose Formation (Benigno of this study), KaLu-Cz is the Walnut Formation (Lagrima of this study) and KamCz is the Edwards Formation (Finlay Formation of this study). Several thrusts indicated but with no offset of stratigraphy. Map covers approximately the same area as Fig. 4.40a

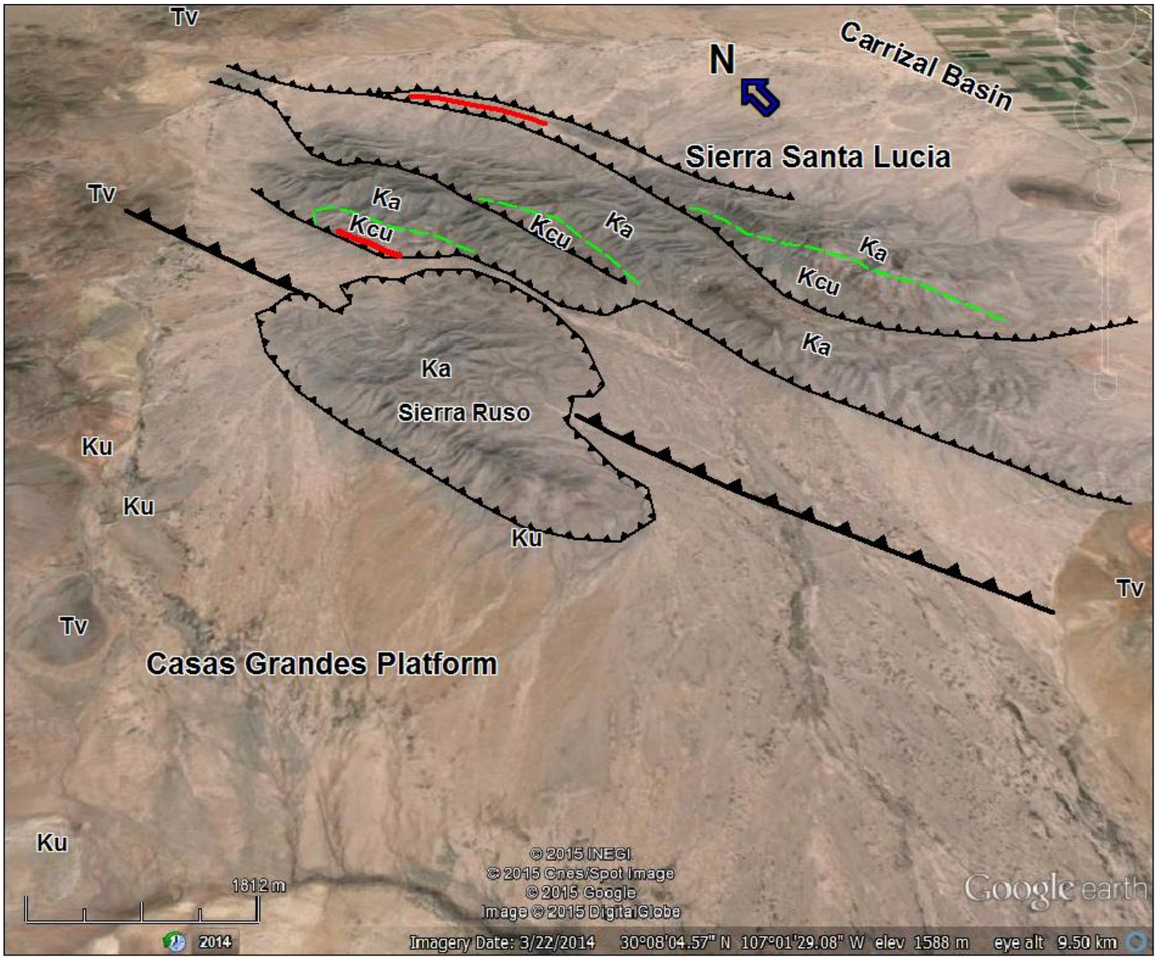
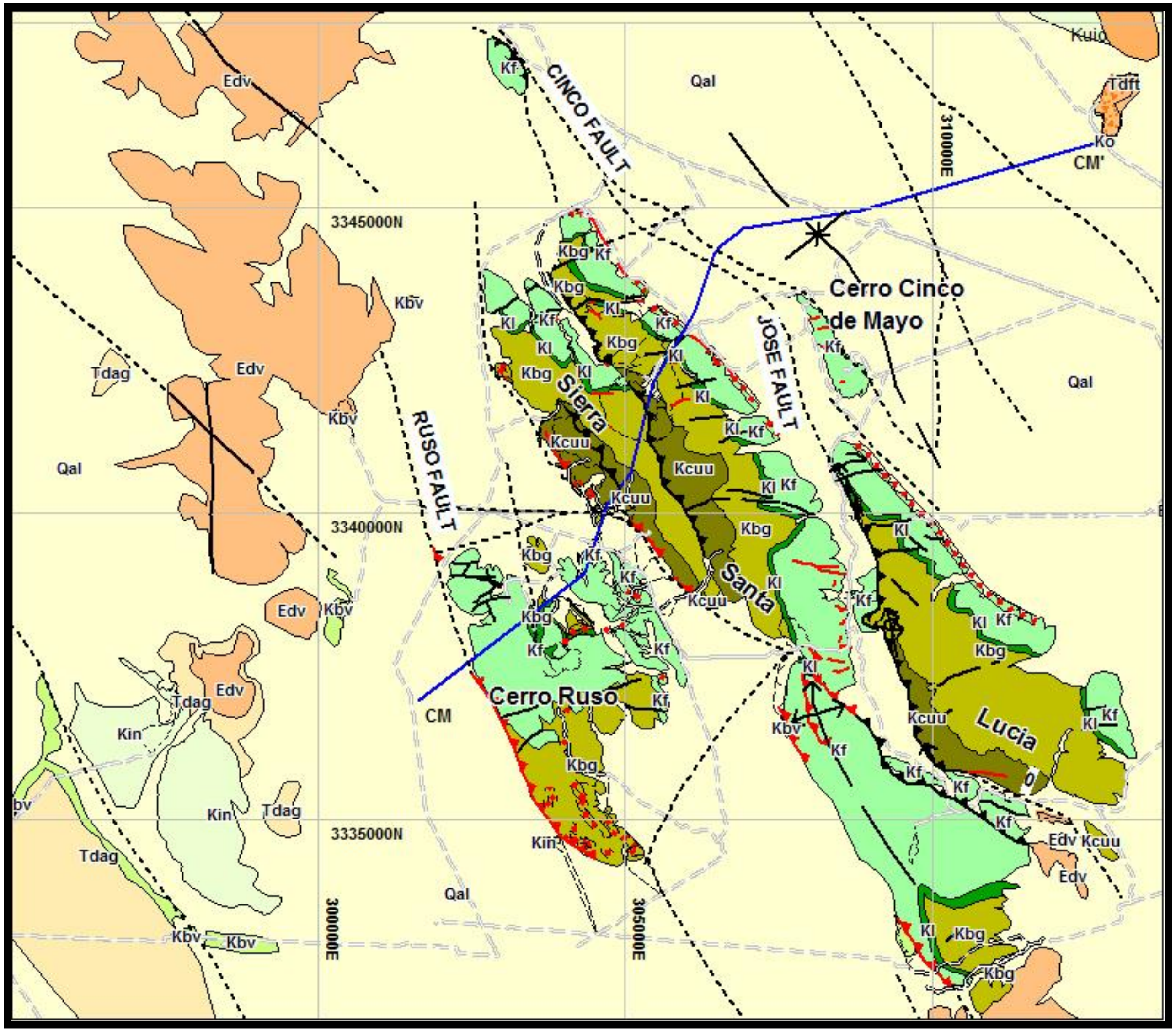


Figure 4.39 Oblique Google Earth view of Sierra Santa Lucia from the southwest showing structural and stratigraphic features.

Map units are Tv- Tertiary volcanic rocks, Ku- Upper Cretaceous strata, Ka-Aurora Group (Chihuahua Group) and the Kcu- Upper Cuchillo Formation. Thrust faults only crop out within the range and the remainder have been documented by drilling. The heavy thrust fault line represents the main inverted fault separating the Carrizal Basin to the northeast and the Casas Grandes Platform to the southwest. The Ku outcrops are weakly deformed Upper Cretaceous of the newly renamed Casas Grandes Platform (formally the Aldama Platform). Sierra Ruso is a klippe off the thrust front that slid on to the platform during thrusting. The recumbent fold in Sierra Ruso indicates it was originally attached to the thrust in the upper right corner of the image.


Edv
Kf
CINCO FAULT
Qal
Kuio
Tdft
31000E
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CM'
3345000N
Kbv
Cerro Cinco
de Mayo
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Edv
JOSE FAULT
Qal
Sierra
Qal
Kbv
RUSO FAULT
Kcuu
3340000N
Santa
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Edv
Tdag
Kin
Cerro Ruso
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3335000N
Tdag
Qal
30000E
30500E
Kbv
Kbv
Kbg
Kf
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Kcuu
Edv
Kcuu
Kin

Fig. 4.40a

Figure 4.40a Geologic map of the Cinco de Mayo District in Sierra Santa Lucia, Chihuahua produced by this study.

The Explanation for the map is Figure 4.40b. District cross section, blue line CM-CM', is Figure 4.41. The 5 km grid is UTM NAD27 zone 13, Mexico.

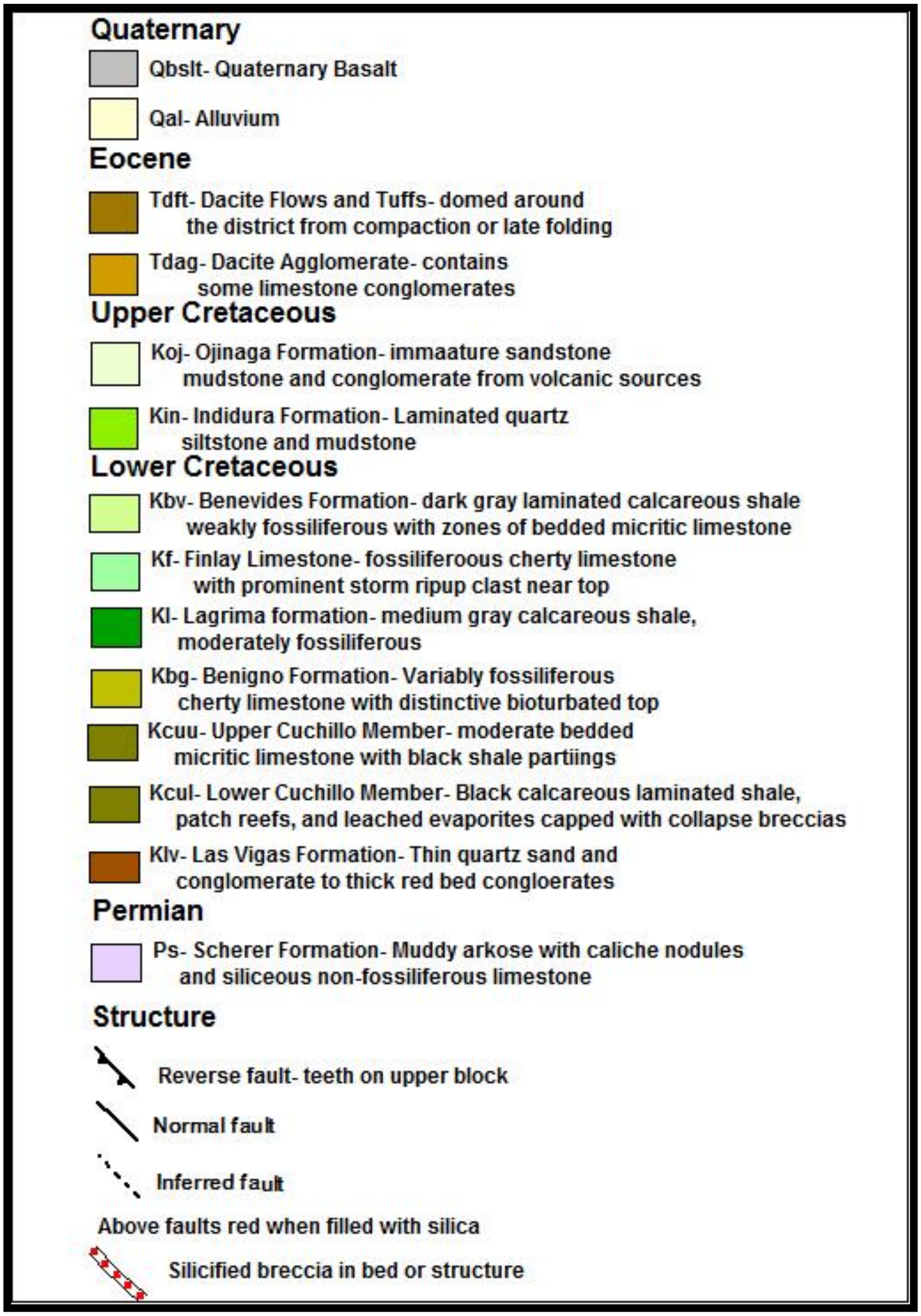

Figure 4.40b Explanation for Cinco de Mayo District, Chihuahua geologic map and cross section.

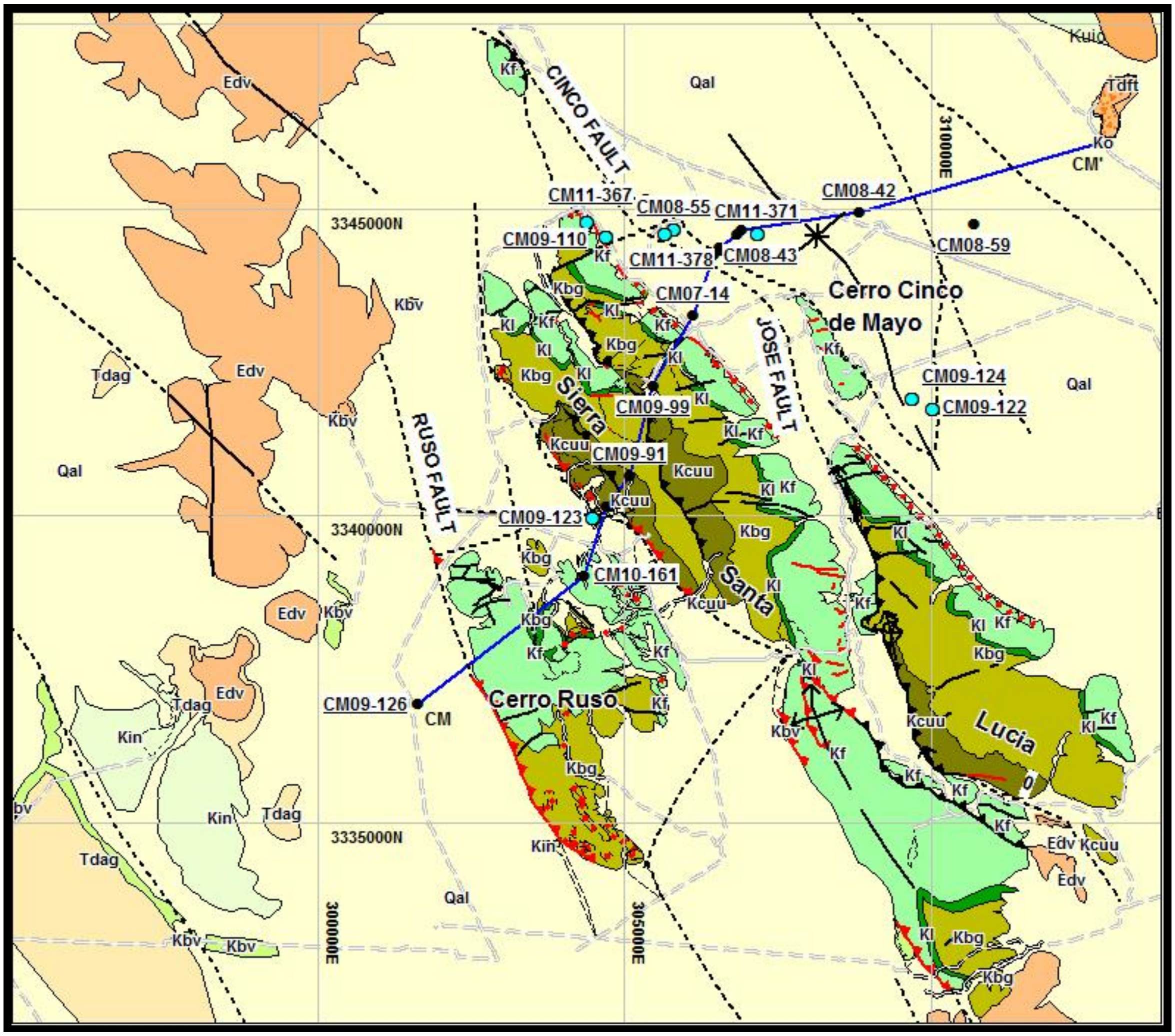

Figure 4.40c Geology with drill holes with core photos in light blue and drill holes used in cross section Fig. 4.40b in black.

CM CM’

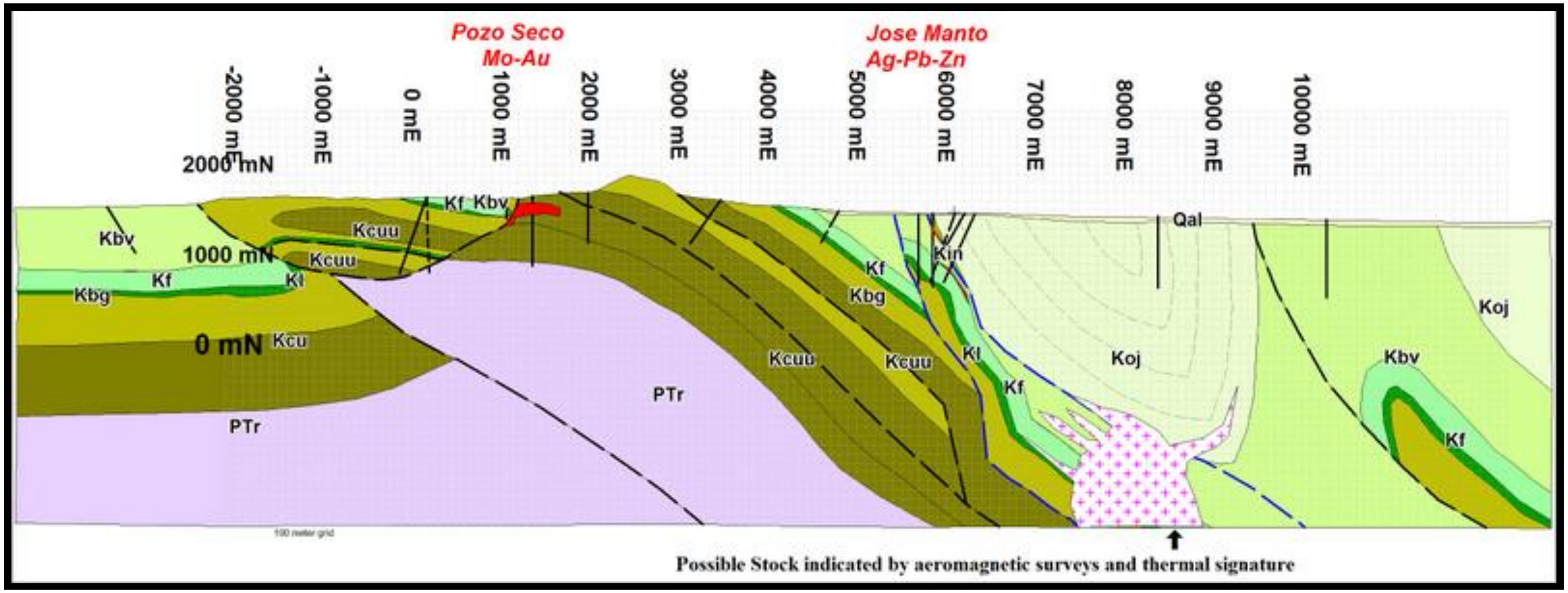

Figure 4.41 The Cinco De Mayo District cross section line CM-CM’ on Figure 4.40a (blue line on map).

Section shows the stacked thrust plates and the detached glide block with recumbent fault propagation fold of Cerro Ruso. Colors and symbols as in Legend (Fig. 4.40b) and purple PTr Permian Scherrer metamorphosed muddy arkose basement. At Sierra Mojina 30 km south southeast contains exposures of Scherrer limestone. Vertical and angle lines from surface down are deeper drill holes used to construct cross-section. (~1,000 m deep). Grid consists of 100 m squares.

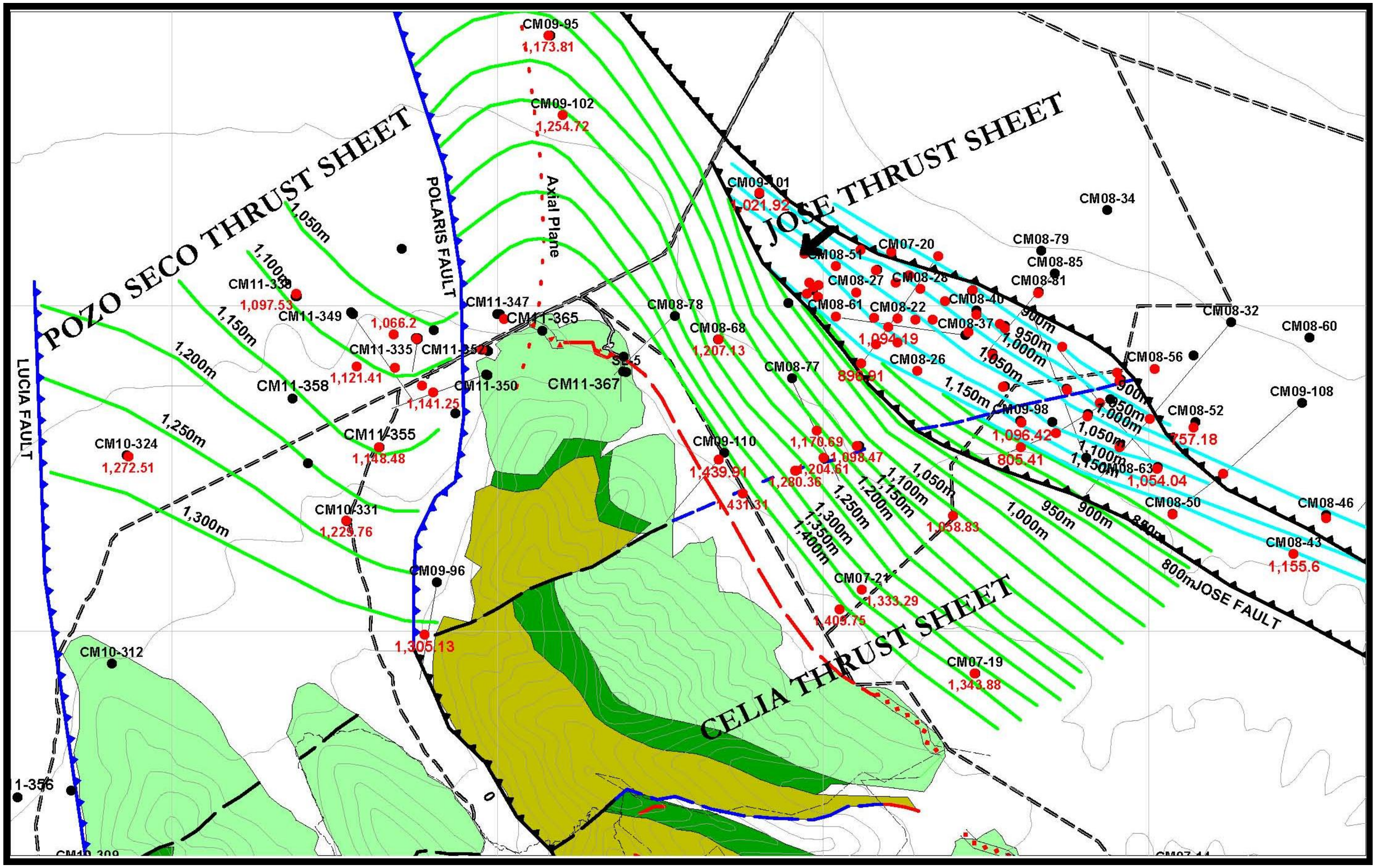
POZO SECO THRUST SHEET
JOSE THRUST SHEET
CELIA THRUST SHEET
POLARIS FAULT
LUCIA FAULT
JOSE FAULT
Axial Plane
CM09-95
1,173.81
CM09-102
1,254.72
CM09-101
1,021.92
CM08-34
CM07-20
CM08-79
CM08-85
CM08-81
CM08-32
CM08-60
CM08-56
CM08-52
757.18
CM09-108
CM08-46
CM08-43
1,155.6
CM08-50
CM08-63
1,054.04
CM09-98
1,096.42
805.41
CM08-26
896.91
CM08-22
1,094.19
CM08-37
CM08-40
CM08-28
CM08-27
CM08-61
CM08-78
CM08-68
1,207.13
CM08-77
CM09-110
1,439.91
1,431.31
1,280.36
1,204.61
1,170.69
1,098.47
1,058.83
CM07-21
1,333.29
1,409.75
CM07-19
1,343.88
CM11-347
CM11-365
CM11-367
CM11-350
CM11-335
CM11-358
CM11-349
CM11-338
1,097.53
1,066.2
1,121.41
1,141.25
CM11-355
1,148.48
CM10-324
1,272.51
CM10-331
1,225.76
CM09-96
1,305.13
CM10-312
1,050m
1,100m
1,150m
1,200m
1,250m
1,300m
1,350m
1,400m
1,000m
950m
900m
850m
800m

Figure 4.42

Figure 4.42 Contour map of the upper surface of the Finlay Limestone constructed from exploration drilling information.

The thrusting of the Jose thrust sheet over the Celia thrust sheet required plotting the top of the Finlay in the Jose thrust sheet light blue to distinguish between the separate plates. The contour curves at the top of the Pozo Seco sheet and the bottom of the Celia sheet reflect the fault bend fold in the respective plates. Red holes intersected Finlay top.

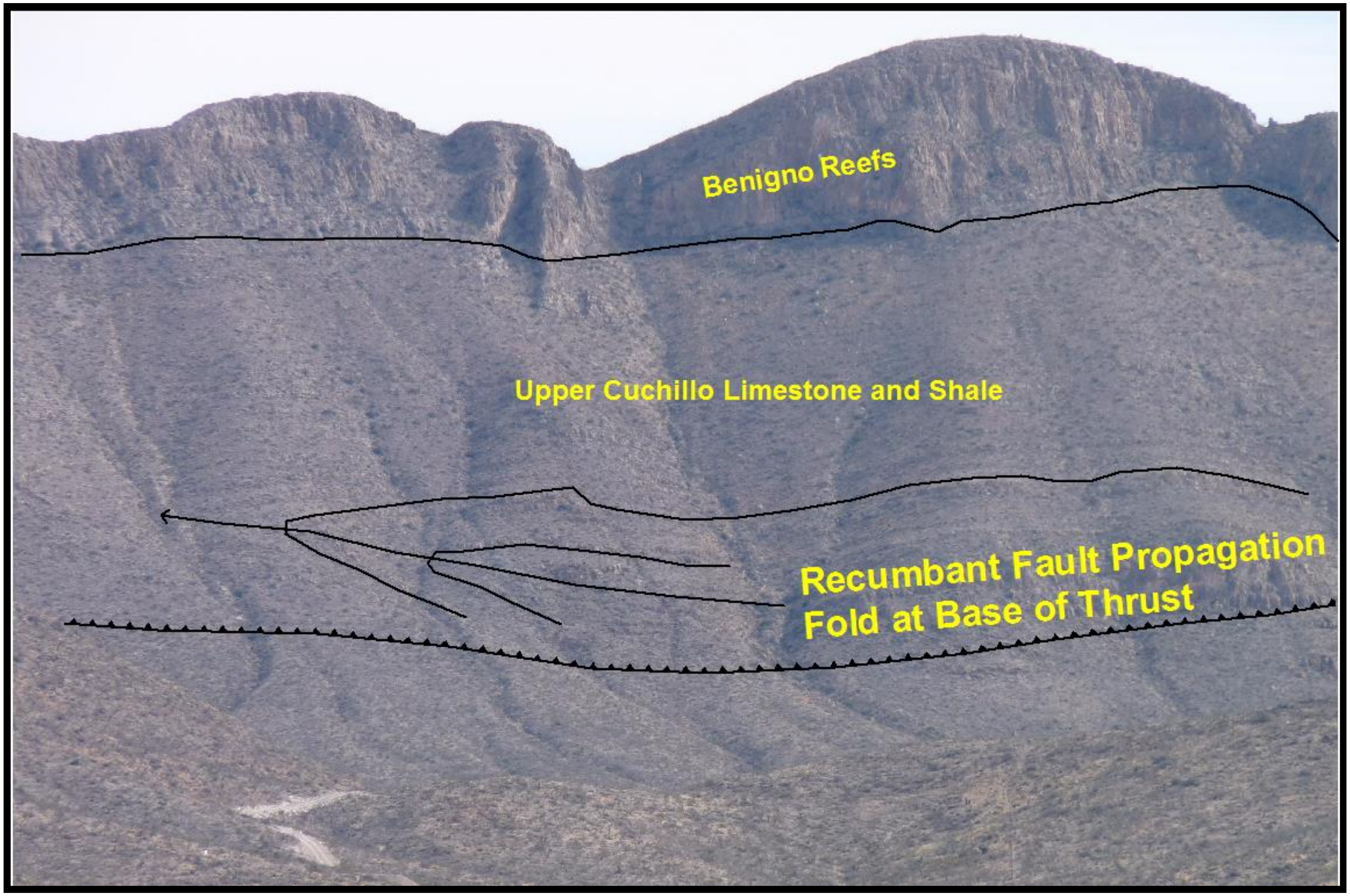

Figure 4.43 Recumbent fault propagation fold above thrust of the southeast ridge of Sierra Santa Lucia looking east.

Fig. 4.43 Benigno reefal limestone caps the Upper Cuchillo Limestone. A recumbent fault propagation fold at the base of the thrust plate is a in Upper Cuchillo that broke into the thrust. Fold is believed to be the root of the recumbent fault propagation fold intersected in Sierra Ruso drilling as it is the only other recumbent fold mapped.

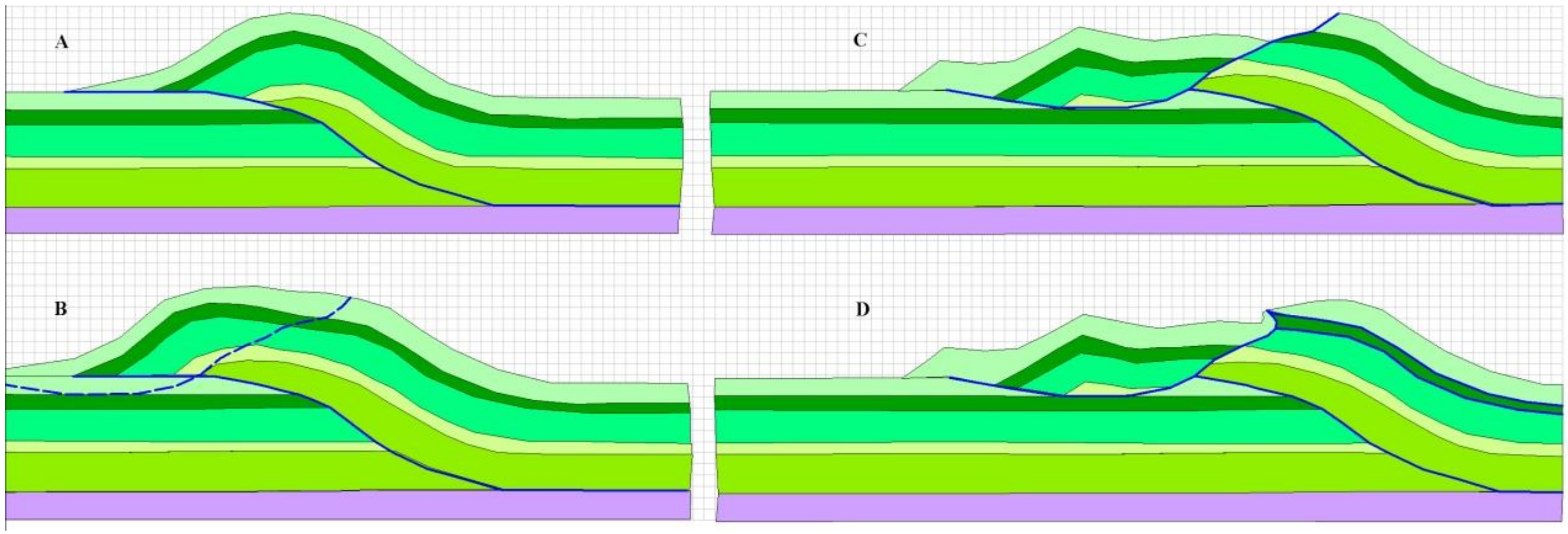

Figure 4.44 Model of origin of Sierra del Ruso slide block from the nose of the south end of the Jose thrust sheet.

Over steepening of the leading edge of the thrust sheet (A, B) that slid across the thrust boundary between the inverted basement block rising up against Casas Grandes Platform to the west (C). Continued shortening of the Carrizal Basin caused the main thrust sheet to fold the normal detachment fault to fold over to the west at the current surface (D) producing an east dipping fault at the surface.

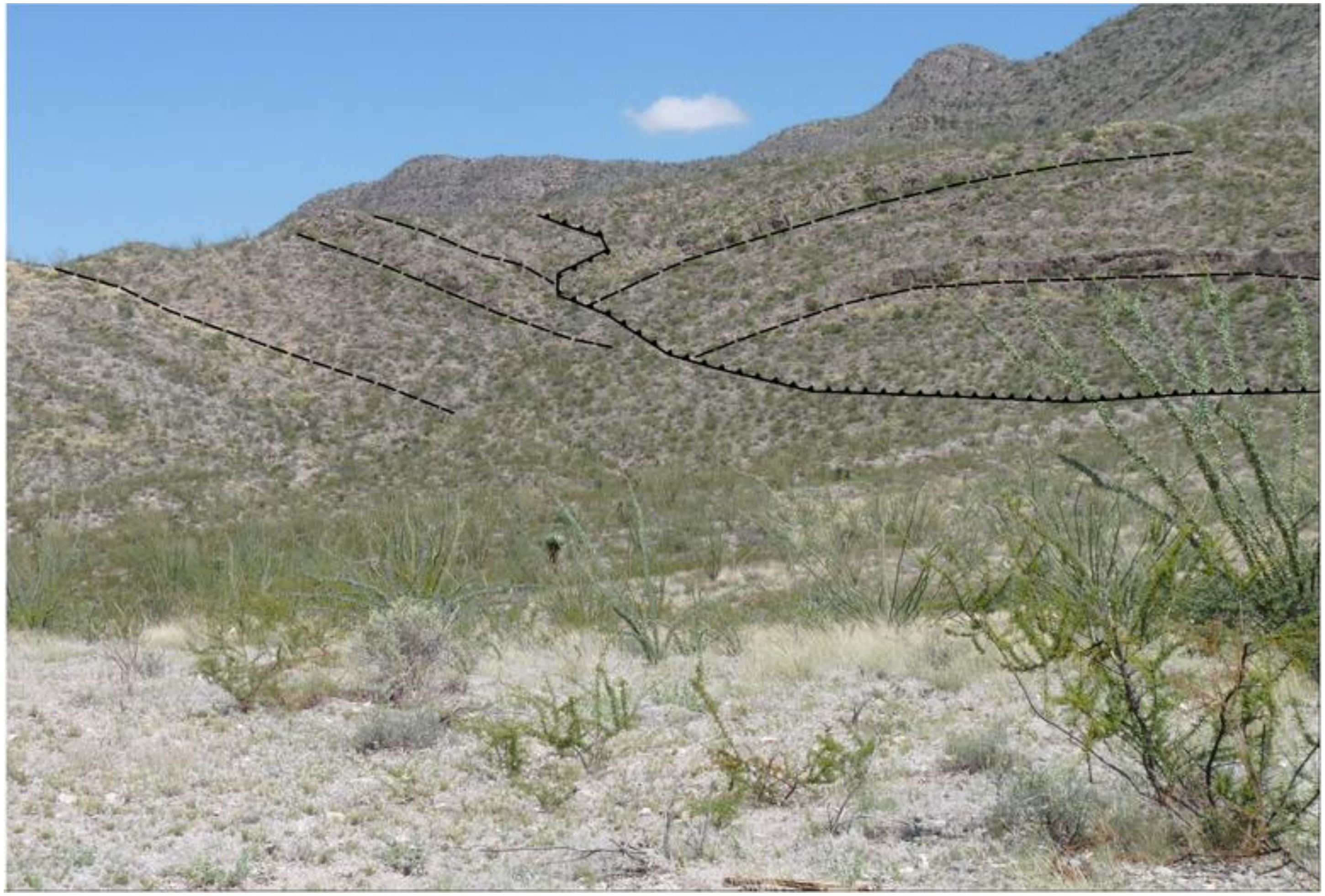

Figure 4.45 A fault-bend fold along the northwest side of Sierra Santa Lucia.

The fault-bend-fold defines one of the intra-formational thrust faults in the Upper Cuchillo Formation.

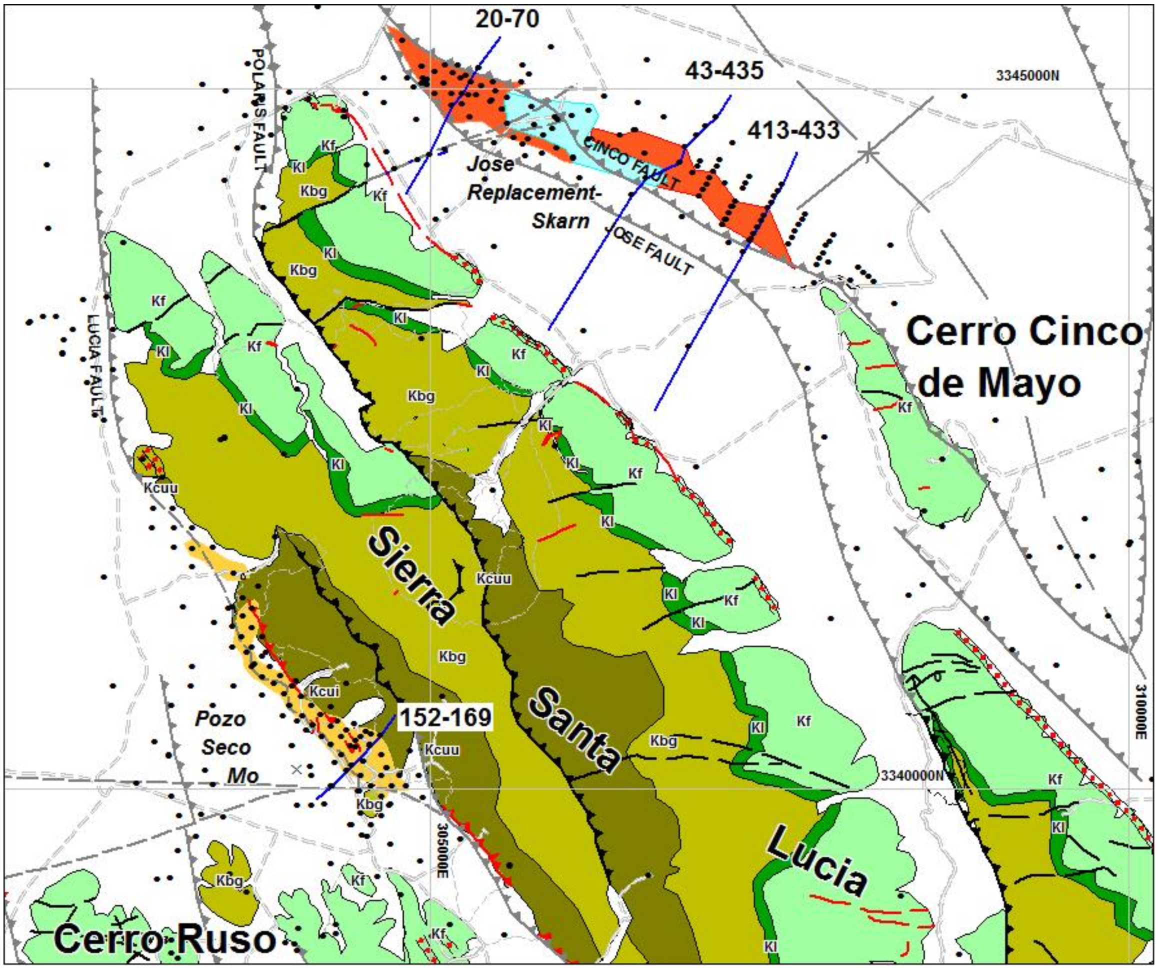

Figure 4.46 Mineral deposits of the Cinco de Mayo District located in the Santa Lucia range.

Deposits include carbonate replacement sulfides (red) with associated hornfels and scheelite skarn (blue) along the northeast margin of the range and a powellite Mo deposit, the Pozo Seco Deposit (golden yellow), along the southwest side of the range. The sulfide replacement (red) continues through the scheelite skarn (blue). Geologic units as Fig.4.40. Cross sections to follow are dark blue lines. The 5 km grid is UTM NAD27 zone 13 Mexico.

SW NE

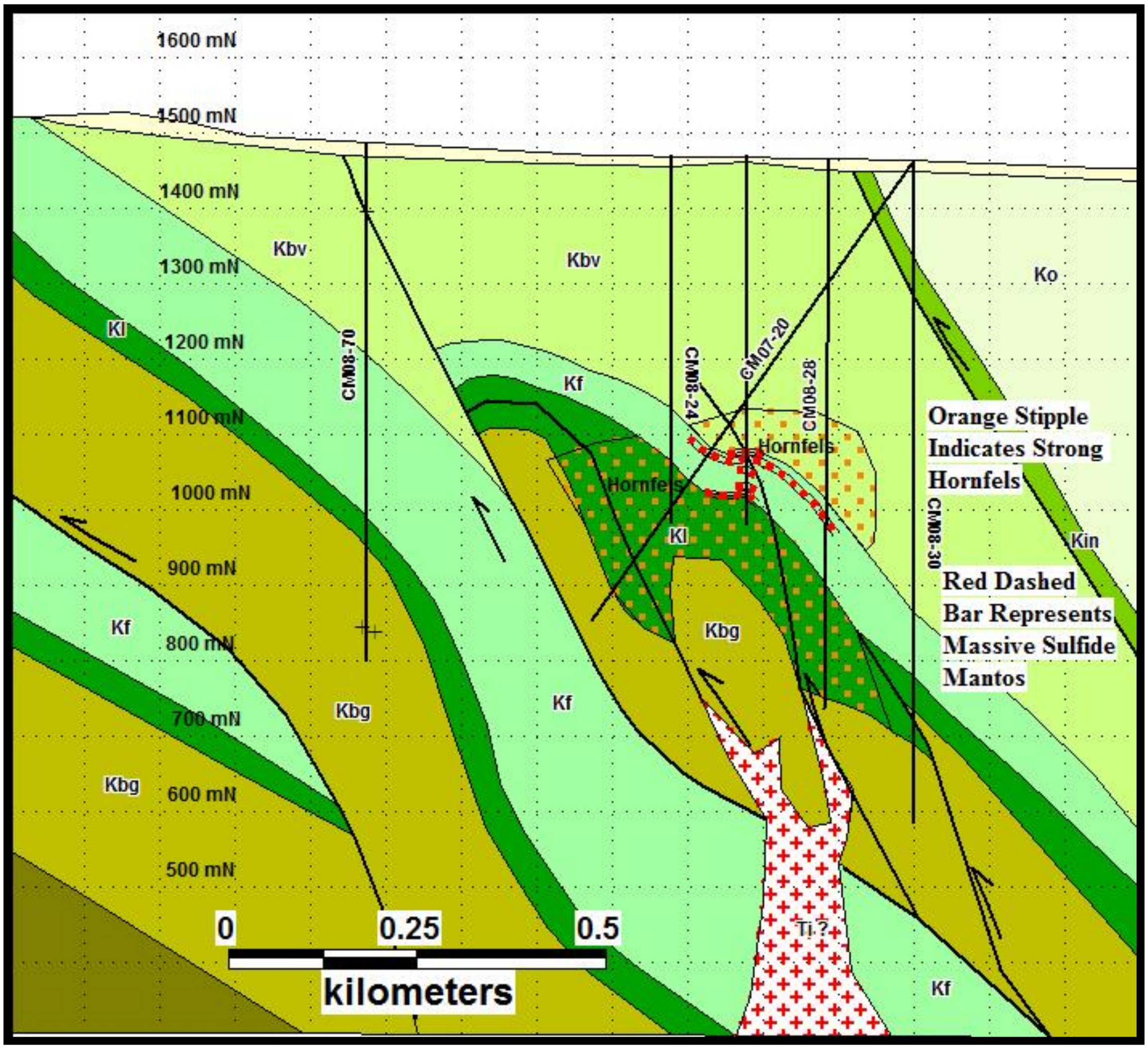

Figure 4.47 Jose Manto discovery drill hole (CM07-20) cross section 20-7 .

Section 20-70 drawn through the discovery hole CM07-20. Strong hornfels in the Benevides and Lagrima chalcareous shales is the strongest silicate alteration observed. Longest mineralized horizon intersected in CM07-20, 22 and 28 corresponds to dissolved rip-up clast bed. Another common mineralized zone is the upper and lower contacts of the Finlay. Geology below the drill holes is speculative.

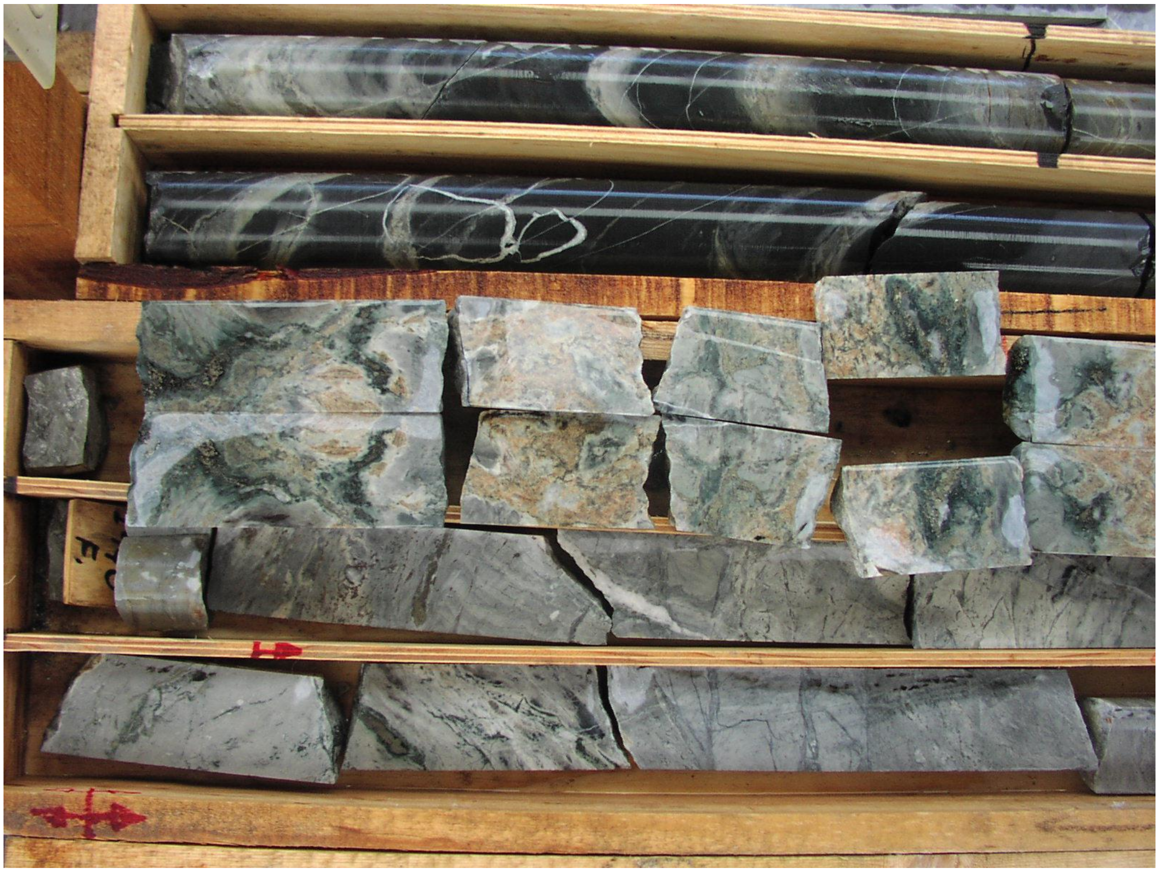

Figure 4.48 Retrograde skarn of hydrogrossularite and chlorite at Finlay-Lagrima Formation contact.

Lagrima shale seen weakly hornfelsed down hole above core from CM08-55 (see location on Fig. 4.40c). Skarn is developed at contact with Finlay limestone. Core is 6.3cm in diameter.

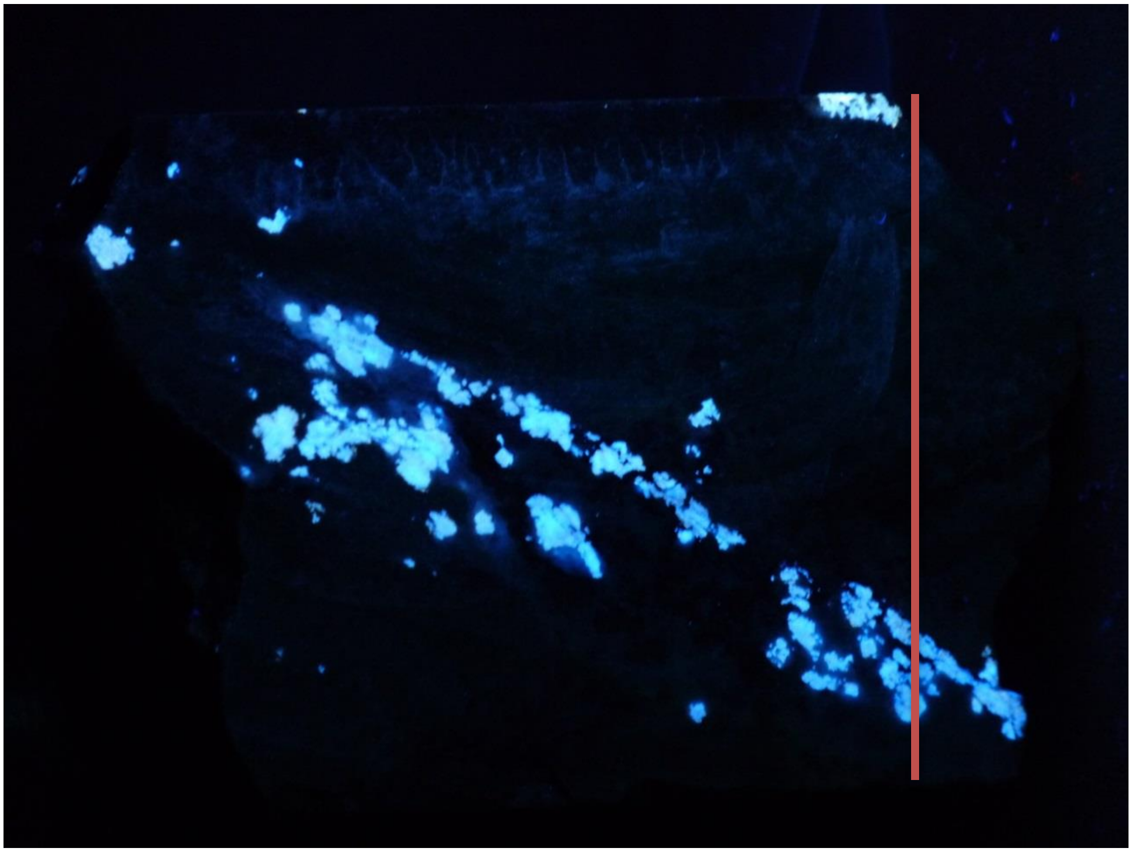

Figure 4.49 Scheelite bearing vein from core.

Vein cuts diagonally across 6.3cm core in shortwave ultraviolet light. Scheelite presence is confirmed by assays. Red line is 6.3 cm long (width of core).

SW NE

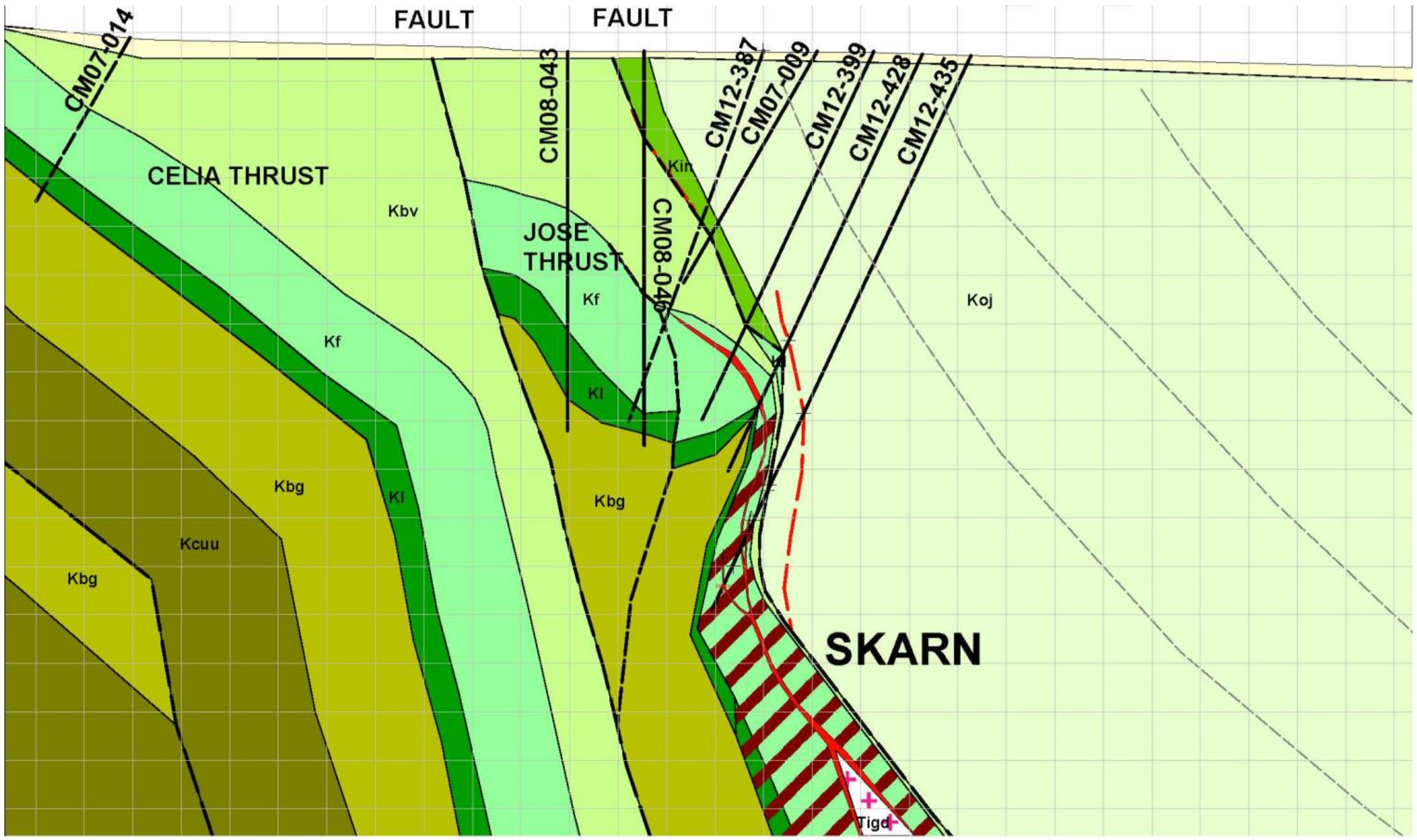

Figure 4.50 Cross section 43-435 showing deep mineralization along rip up clast horizon and the development of back thrusting in skarn zone.

The intrusion is inferred from skarn intensity and aeromagnetic data. The grid consists of 100 m squares.

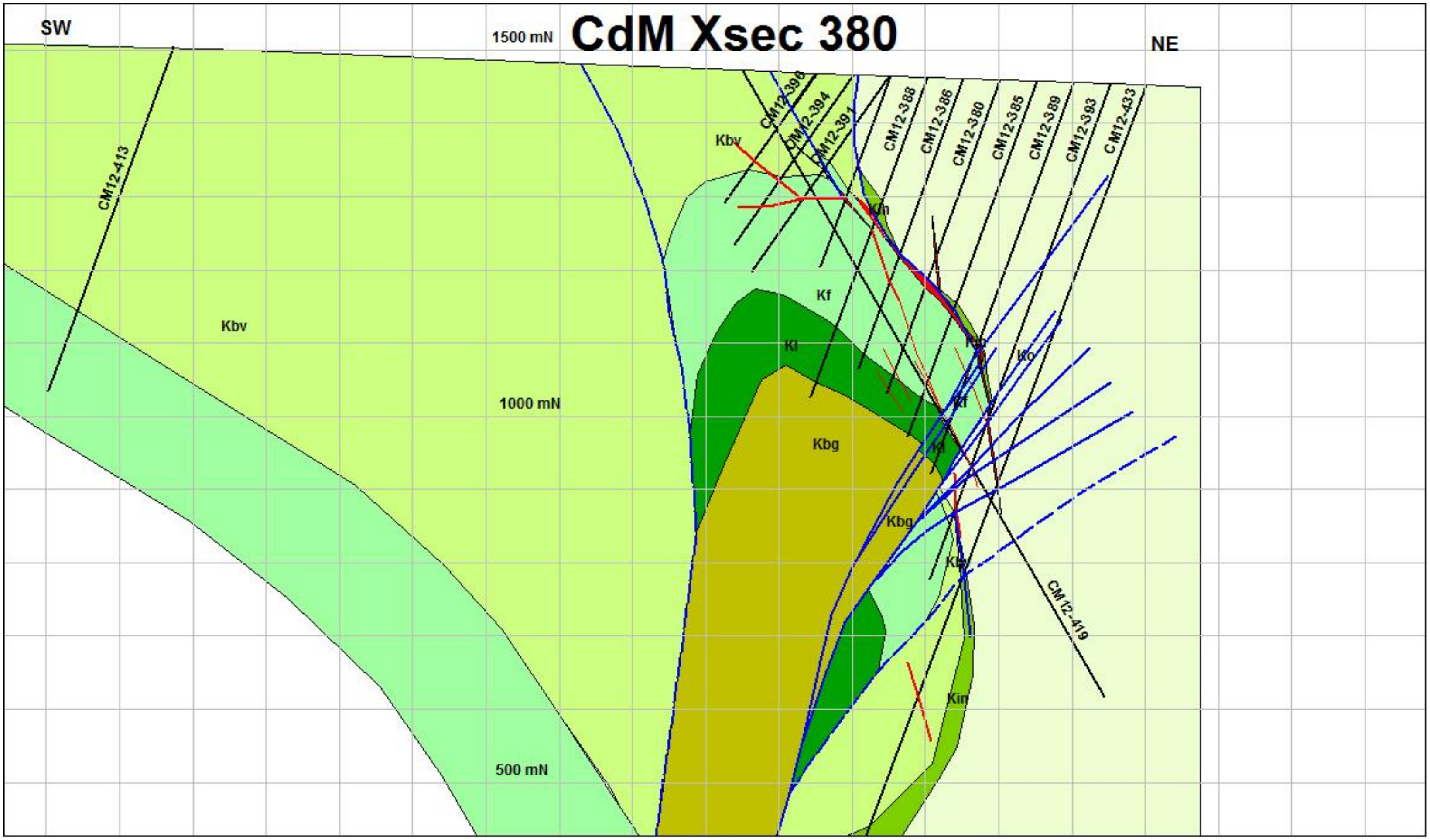

Figure 4.51 Cross section 413-380-433 illustrates the extreme back thrusting along the southern part of the ore body.

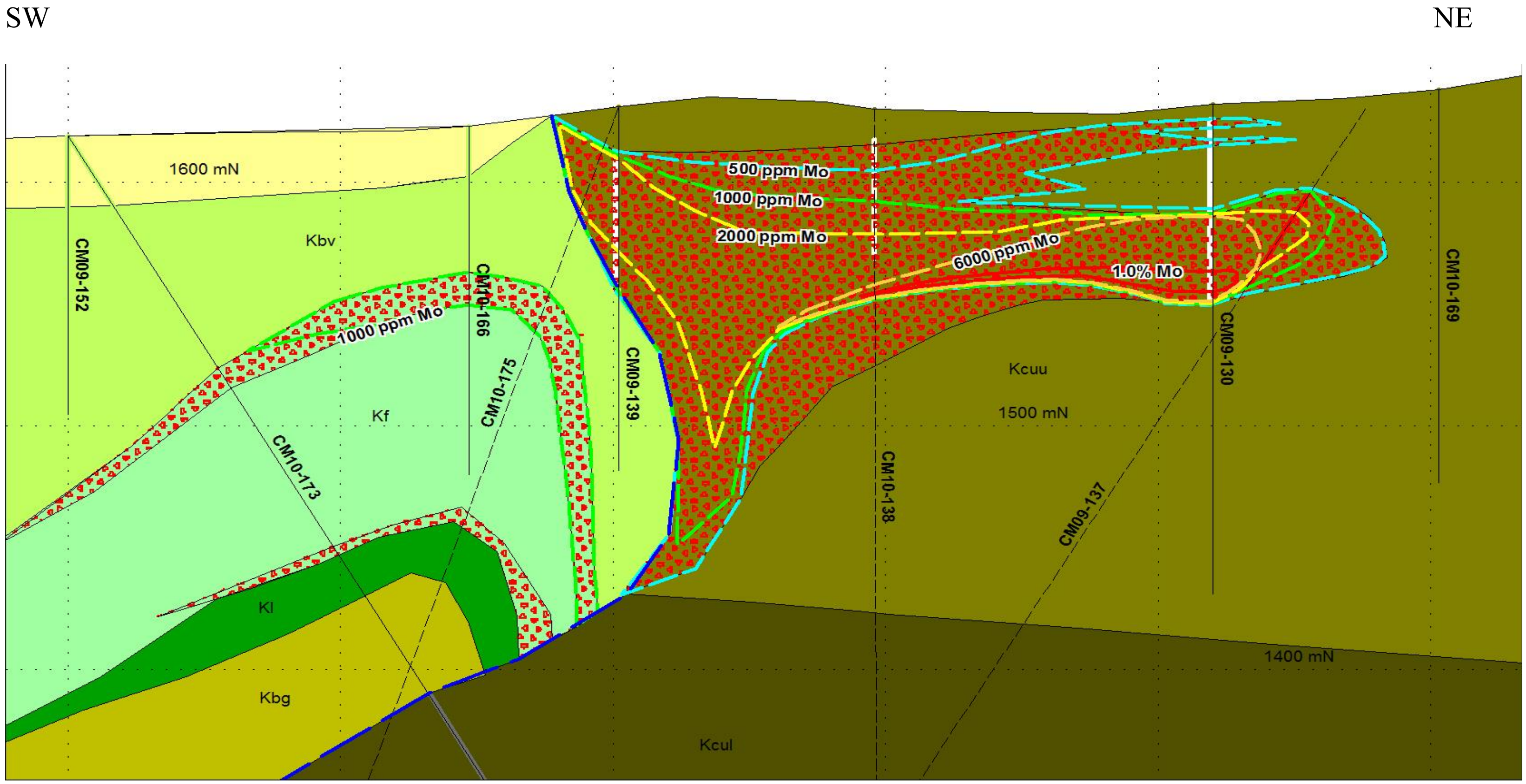

Figure 4.52 Cross section 152-169 cuts through the south end of the Pozo Seco Mo Deposit.

After the large klippe broke free and slid on to the Casas Grandes Platform thrusting continued along faults within the Upper Cuchillo causing it to push out over the klippe inverting the normal fault beneath the klippe. Mineralization less than 2,000 ppm Mo mineralization observed along Finlay contacts in upper plate.

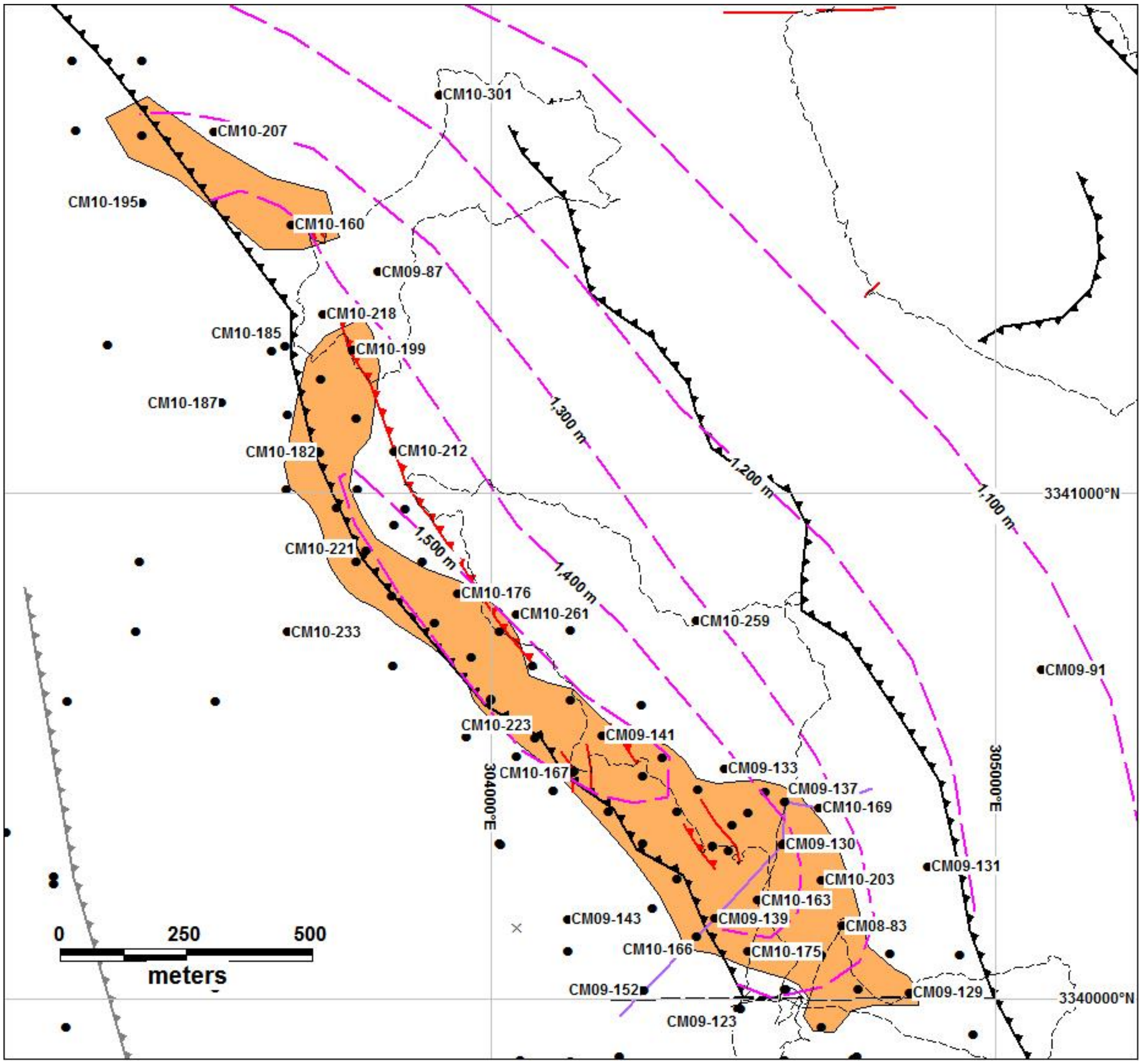

Figure 4.53 Plot of the Upper Cuchillo-Lower Cuchillo contact under the Pozo Seco Mo deposit.

It shows the elongate doming on this surface that corresponds very closely to the distribution of the Mo deposit shown in orange. Cross section 152-169 of Fig. 4.53 marked by the purple line.

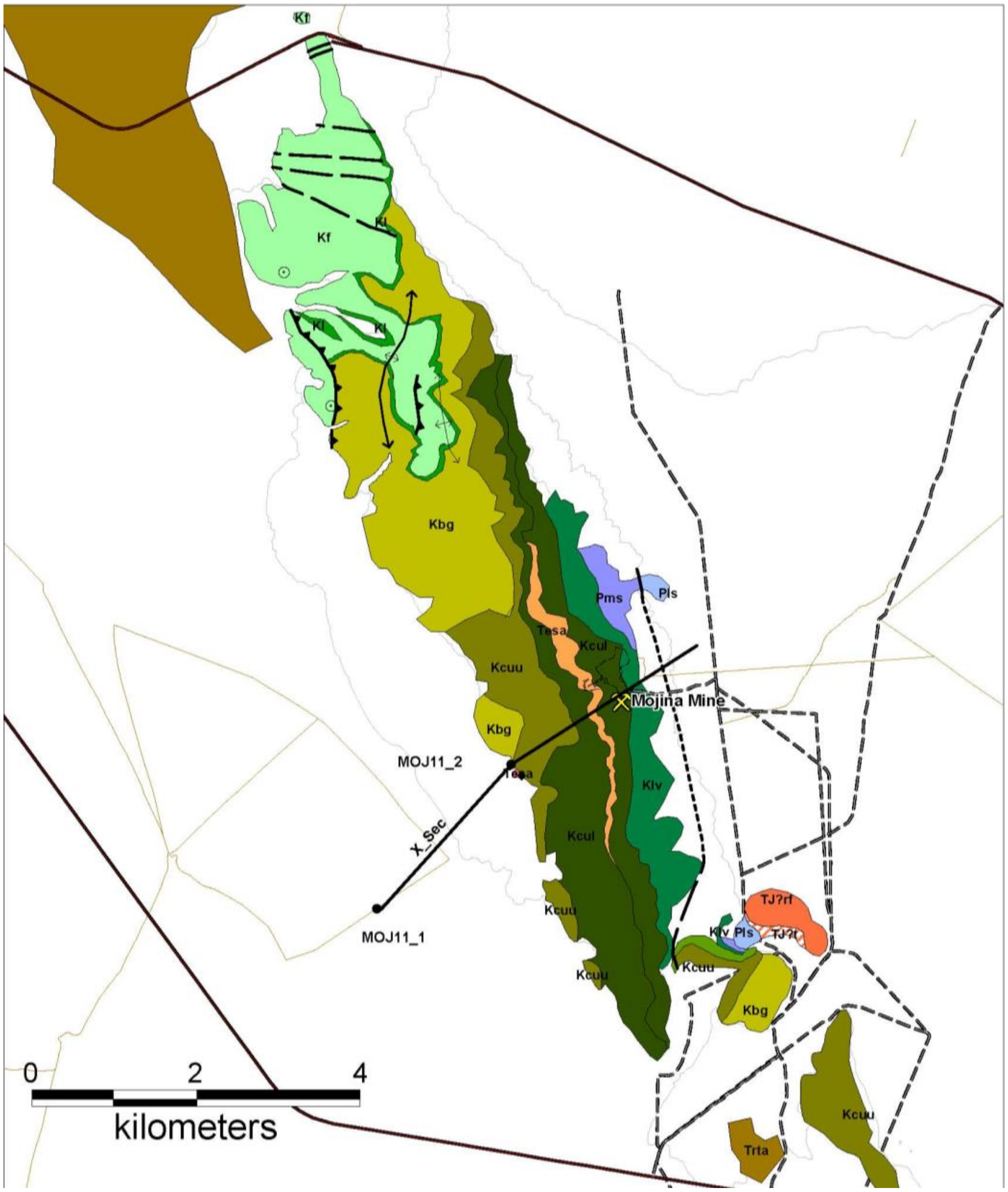

Figure 4.54 Geology map of Sierra Mojina located 30km south southeast of Sierra Santa Lucia.

The Lower Cretaceous section of Las Vigas (Klv), Lower Cuchillo (Kcul), Upper Cuchillo (Kcuu), Benigno (Kbg), Lagrima (Kl) and Finlay is exposed in a WSW directed fault-bend fold. The core of the underlying inverted basement block consists of Permian Scherrer Arkose Pms overlying fossil poor Scherrer Limestone.Pls. Unmapped fresh diabase sills are common in the lower part of the Lower Cuchillo. An altered silicic sill (Tesa) is closely associated with mineralization found along its contacts and was intersected in MOJ11-2. Margins are north and east trending lines.

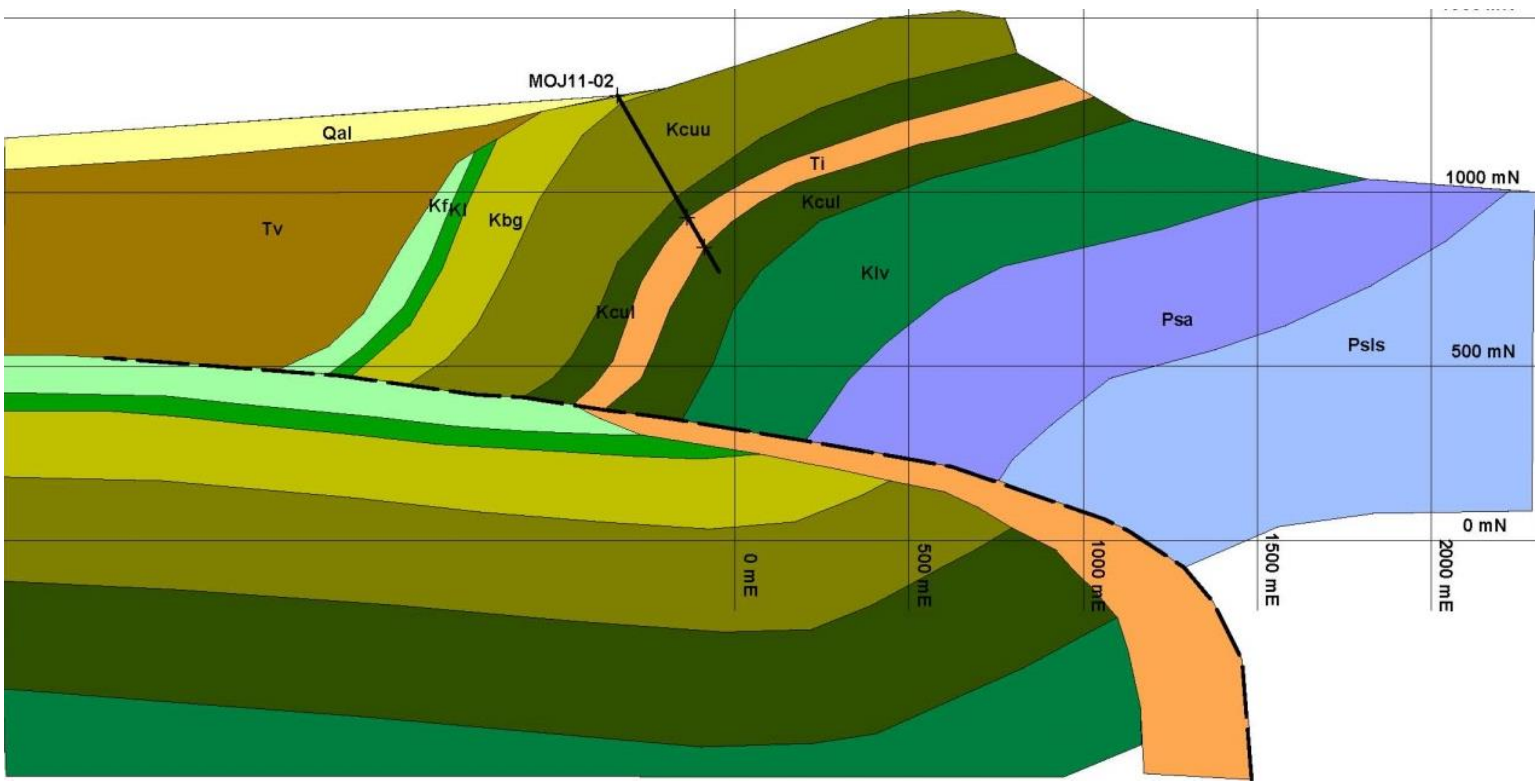

Figure 4.55 Sierra Mojina cross section through drill hole MOJ11-2.

Section shows the fault-bend fold that forms the crest of the Mojina ridge and possible source of the silicic sill that intrudes the Lower Cuchillo. This interpretation is derived from projecting the fully exposed fault-bend fold in the north end of the range south through MOJ11-2. Grid is 500m.

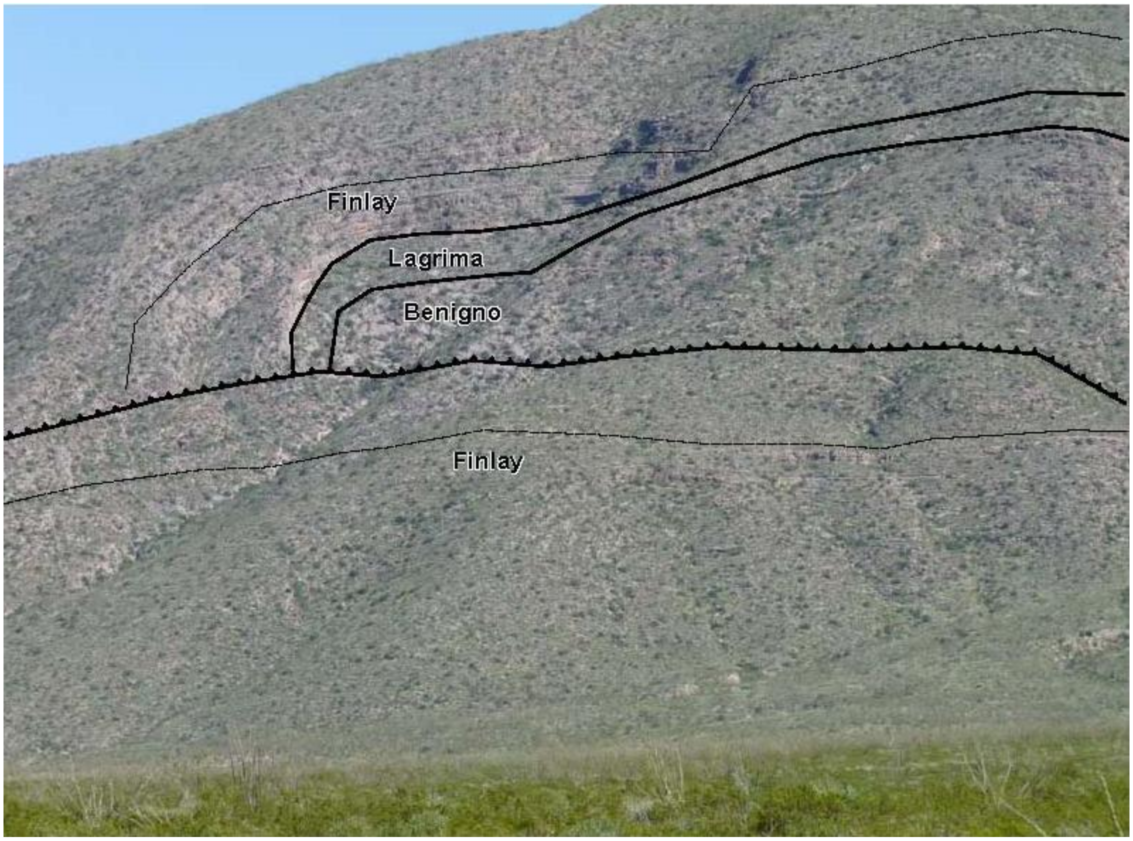

Figure 4.56 Fault-bend-fold central west side of Sierra Mojina.

Sierra Mojina range showing the nose of the west-directed fault-bend fold that is well exposed along on the central west side of the range. Brush on the limestone slopes typically one meter high.

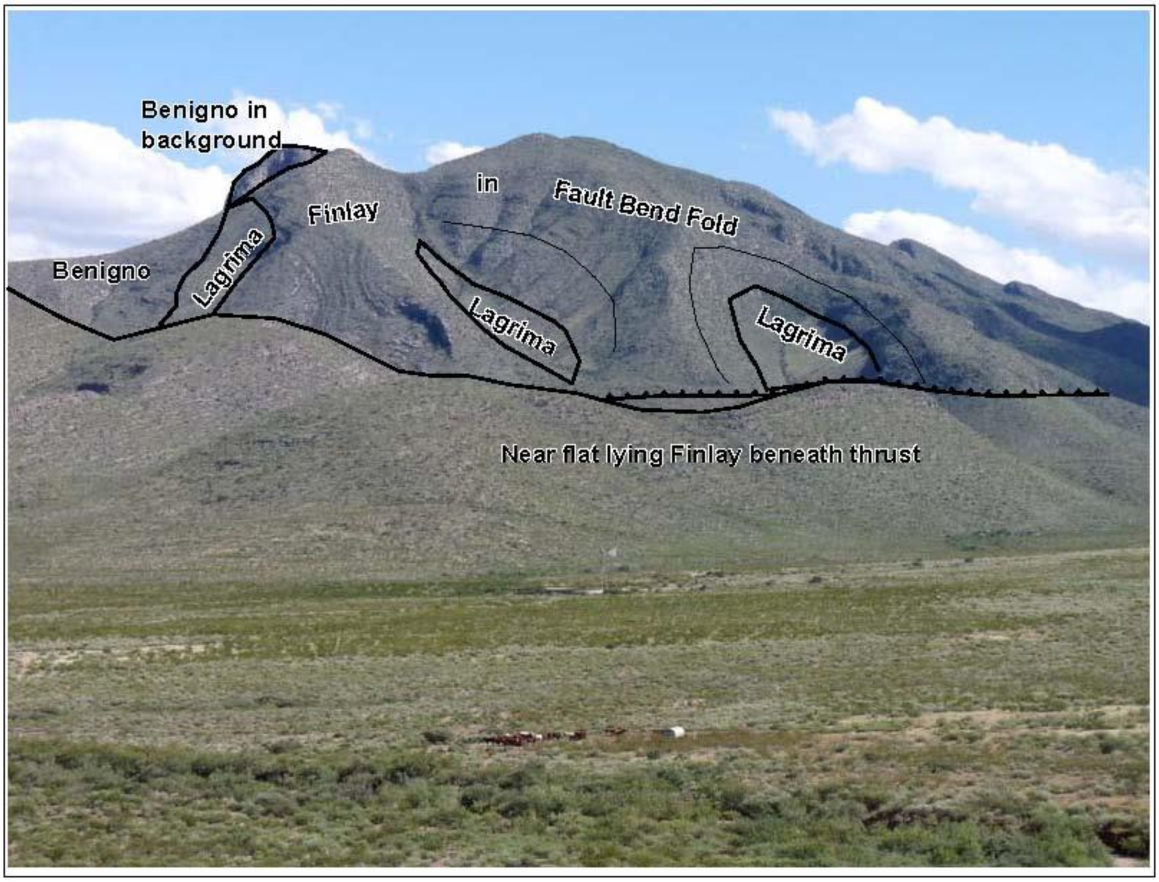

Figure 4.57 North end of Sierra Mojina looking southeast into north end of fault-bend fold.

Figure 4.58 Simplified geology of Sierra Banco de Lucero plotted on an oblique Google Earth image of the range looking southwest.

Unit labels are the same as for Cino de Mayo.

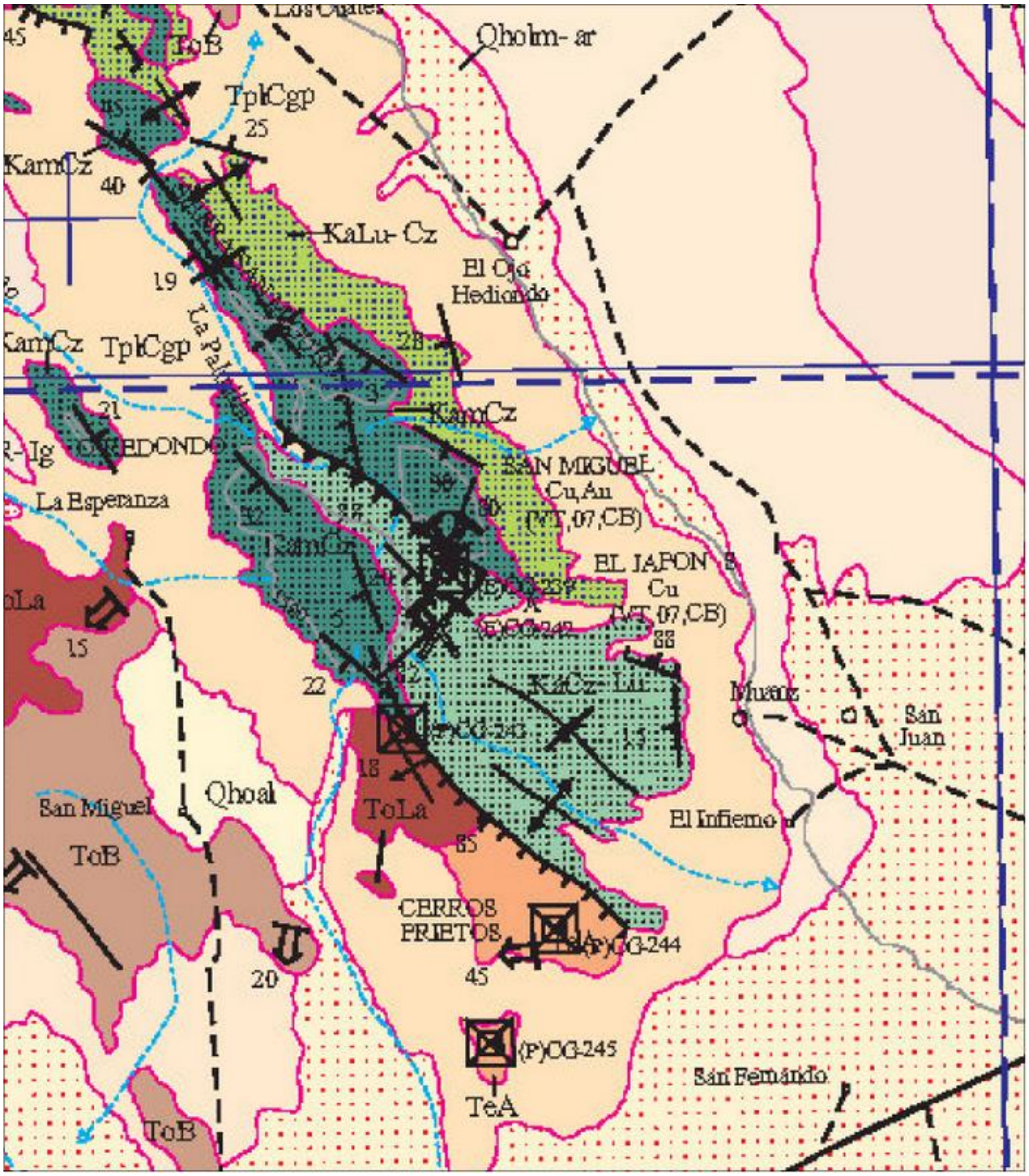

Figure 4.59 The published map of Sierra Banco Lucero (Hernandez-Velazquez and others, 2002) uses Texas stratigraphic nomenclature and recognizes the low angle fault separating the two ridges of Banco Lucero.

They label the limestone capping both ridges as KamCz (Edwards equals Finlay in this study) but place KaCz-Lu (Kiamichi equals Benevides in this study) beneath the unit labeled KamCz in the southwestern ridge. This is an inversion from normal stratigraphic order even in their explanation. In the northeastern ridge they map KaLu-Cz (Walnut equals Lagrima in this study) beneath the KamCz a normal stratigraphic sequence. Monreal and Longoria do not recognize an inverted stratigraphic sequence here.

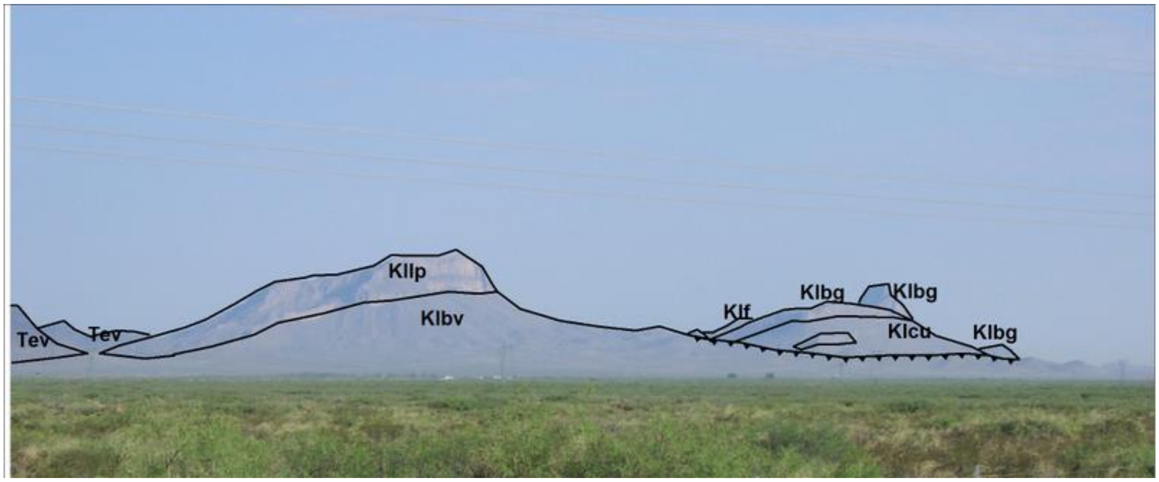

Figure 4.60 A photo of Sierra Banco Lucero marking the units as mapped in this study.

In the northeast ridge Klcu is the Upper Cuchillo Formation at the base of the exposed section capped by Klbg or Benigno Formation, Klf or Finlay Limestone (Lagrima that separates Benigno and Finlay not visible in this photo). Above the low angle fault, the base of the southwest ridge consists of Klbv or Benevides Formation that is capped by Kllp or Loma Plata Formation.

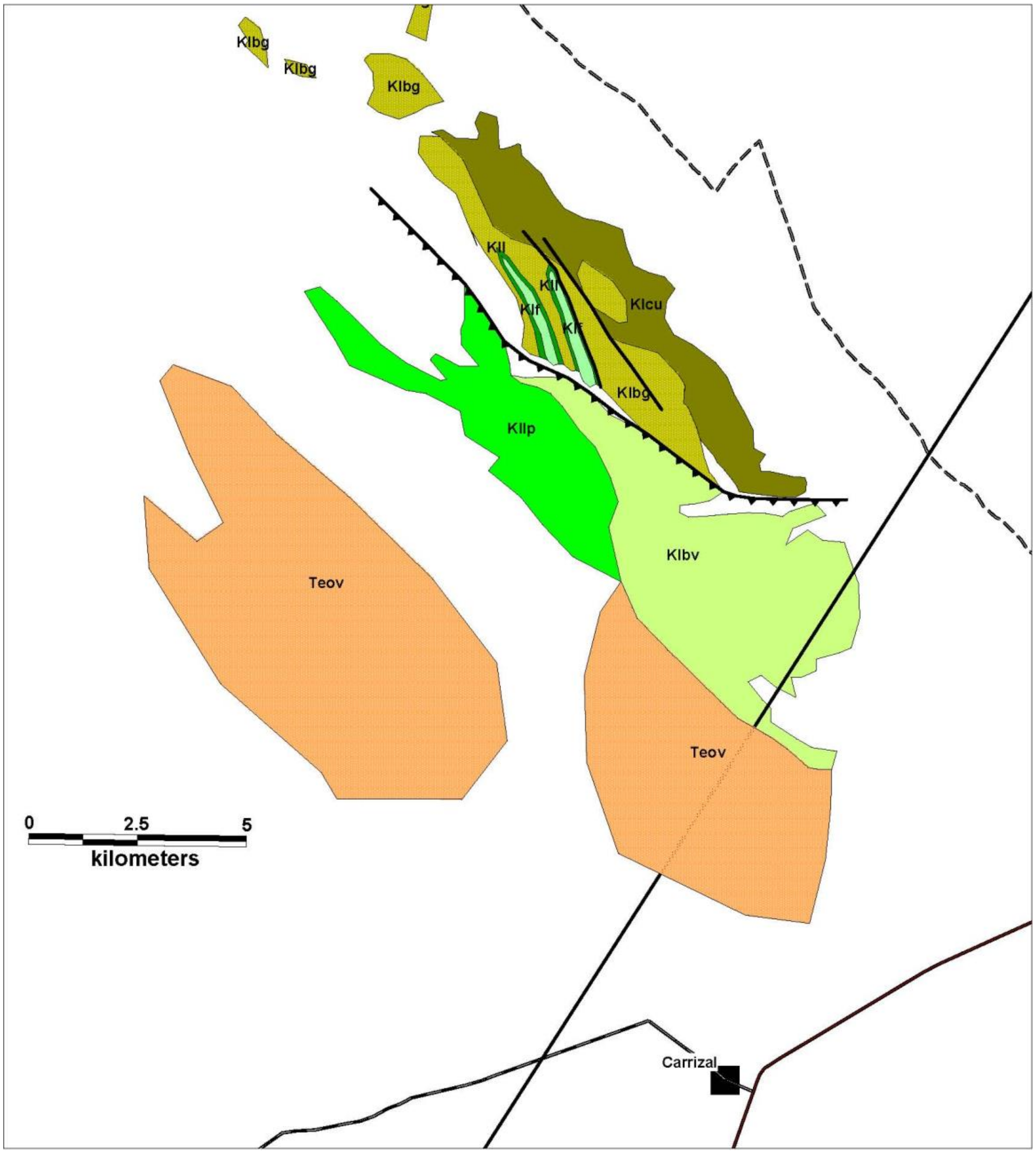

Figure 4.61 The reconnaissance geologic map of Sierra Banco Lucero produced as a part of this study.

Units are as in Figure 4.60 with the addition of Kll or Lagrima Formation. The Benigno-Lagrima-Finlay part of the stratigraphy appears to be faulted out at the southeast end of the area by the low angle fault. Much of the Benevides is faulted out at the northwest end of the range while the Benigno-Lagrima-Finlay section is not. There may be a fault between the two Finlay-Lagrima ridges but it was not observed in the field.

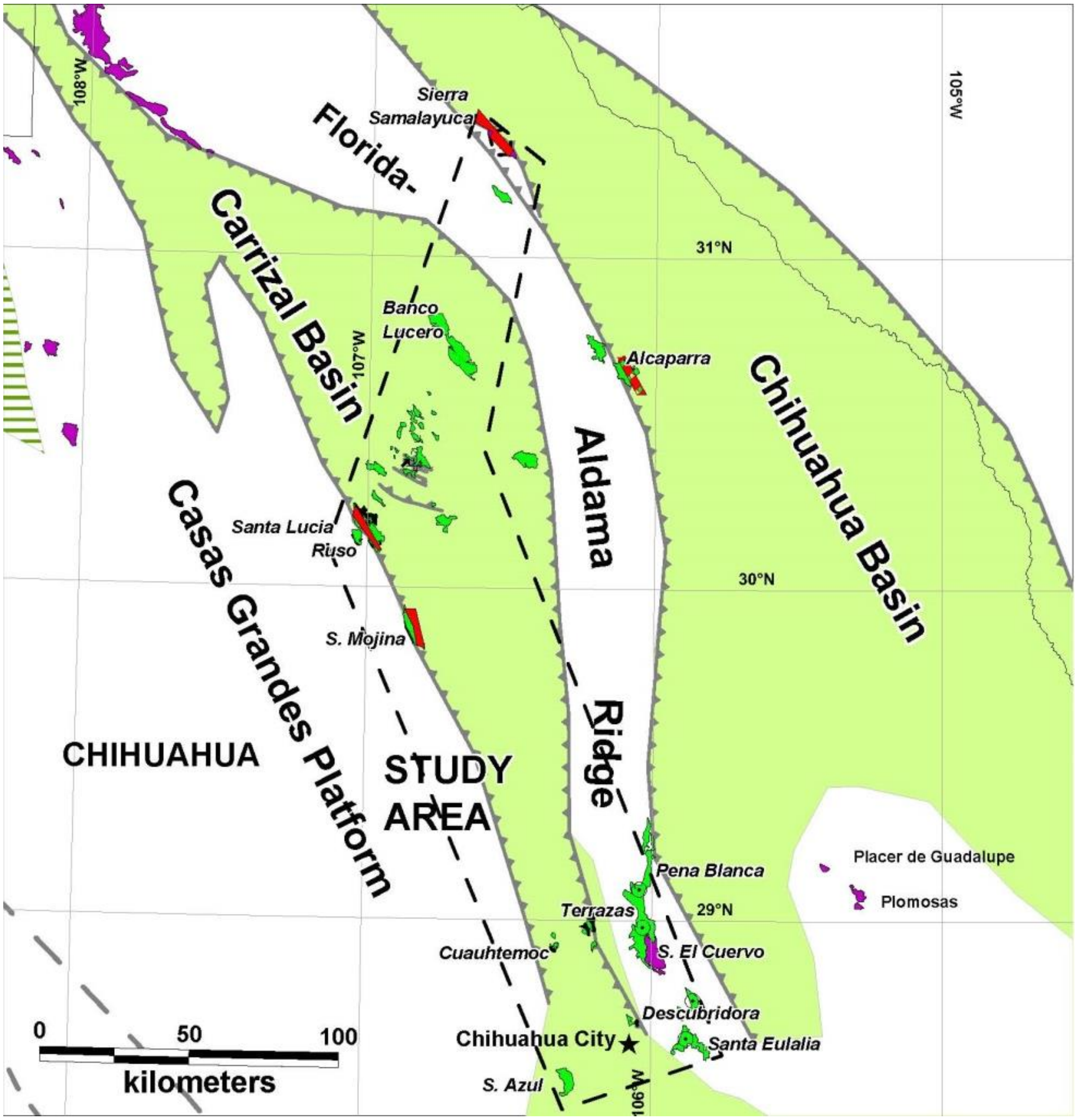

Figure 4.62 Regional location map indicating study area (dashed outline) and the proposed Carrizal Basin west of the Chihuahua Basin.

Gray toothed outline indicates the direction of thrusting out-of-the-basin (teeth on upper plate). Cities and villages are labeled with non-italic letters and outcrops of importance to the study are labeled with italics. The important structural features are labeled with larger italic letters. The Cretaceous outcrops are in bright green, and Permian outcrops in purple. Red bands indicate documented and inferred inverted basement blocks along basin margins.

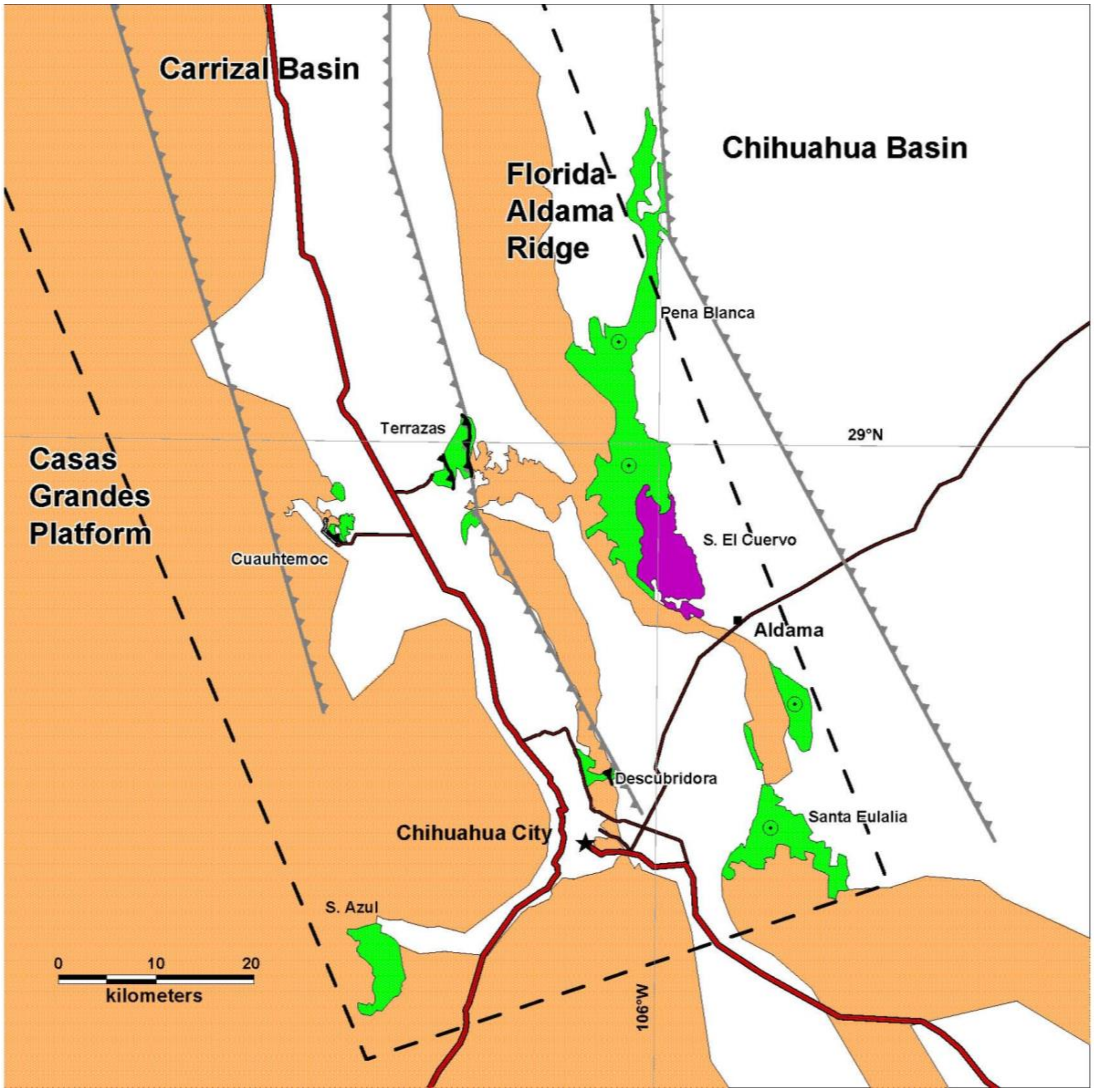

Figure 4.63 South Carrizal Basin reconnaissance geologic map.

The map shows the east-directed thrusting mapped at Terrazas and Descubridora and the west-directed fault-bend fold at Cuauhtemoc (Salemex). The Aurora Group limestones at Sierra Peña Blanca through Santa Eulalia are mostly flat lying. The limestones at Sierra Azul are deformed but not yet mapped but from an over flight it appears to be a west-southwest-directed fault-bend fold. This bidirectional thrusting delineates the continuation of the Carrizal Basin into the Chihuahua City area.

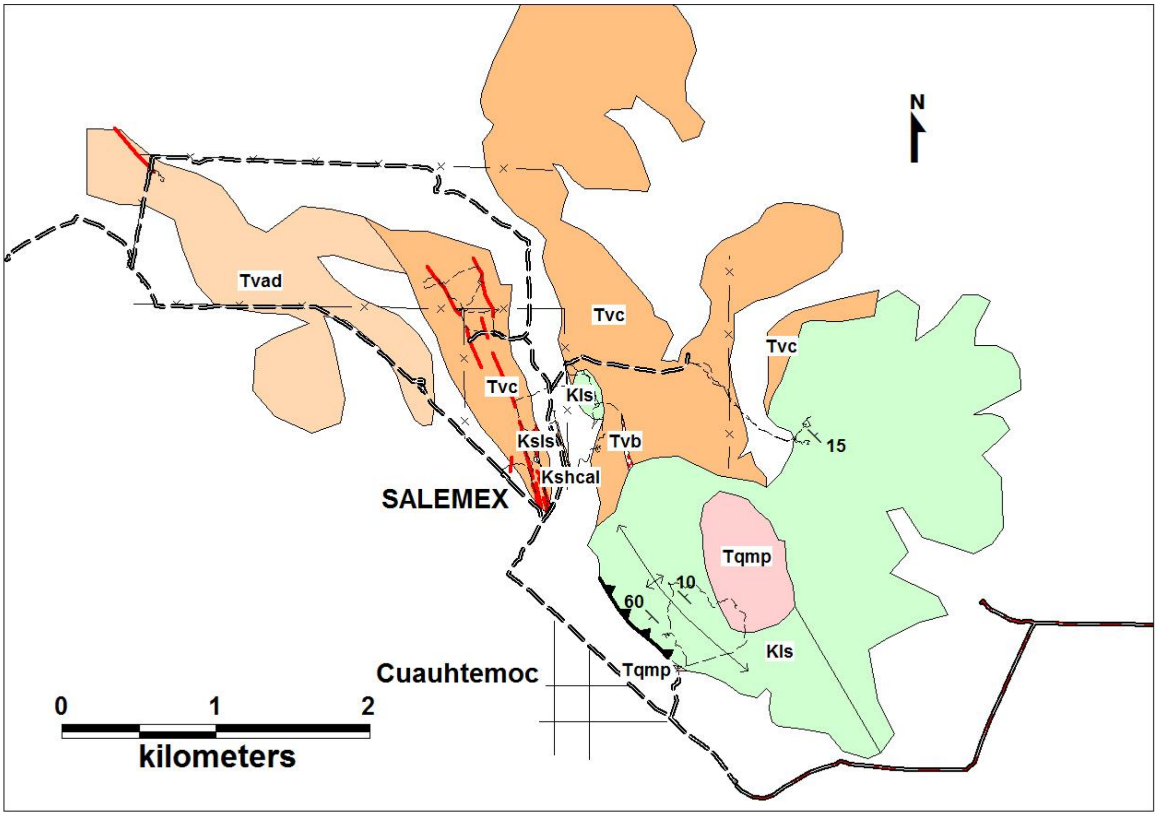

Figure 4.64 Aurora Group limestones on reconnaissance geologic map of the Salemex Project north of the village of Cuauhtemoc, Chihuahua.

At the northeast edge of Cuauhtemoc, the Aurora Group limestone displays a southwest-directed fault bend fold. Veins with scattered prospect pits shown as red lines in volcanic rocks. Units are Kls-Aurora Group limestones, Tvc- Tertiary volcanic agglomerate, Tvad- Tertiary dacite, Tvb- Tertiary subvolcanic breccia, Tqmp- Tertiary quartz monzonite porphyry.

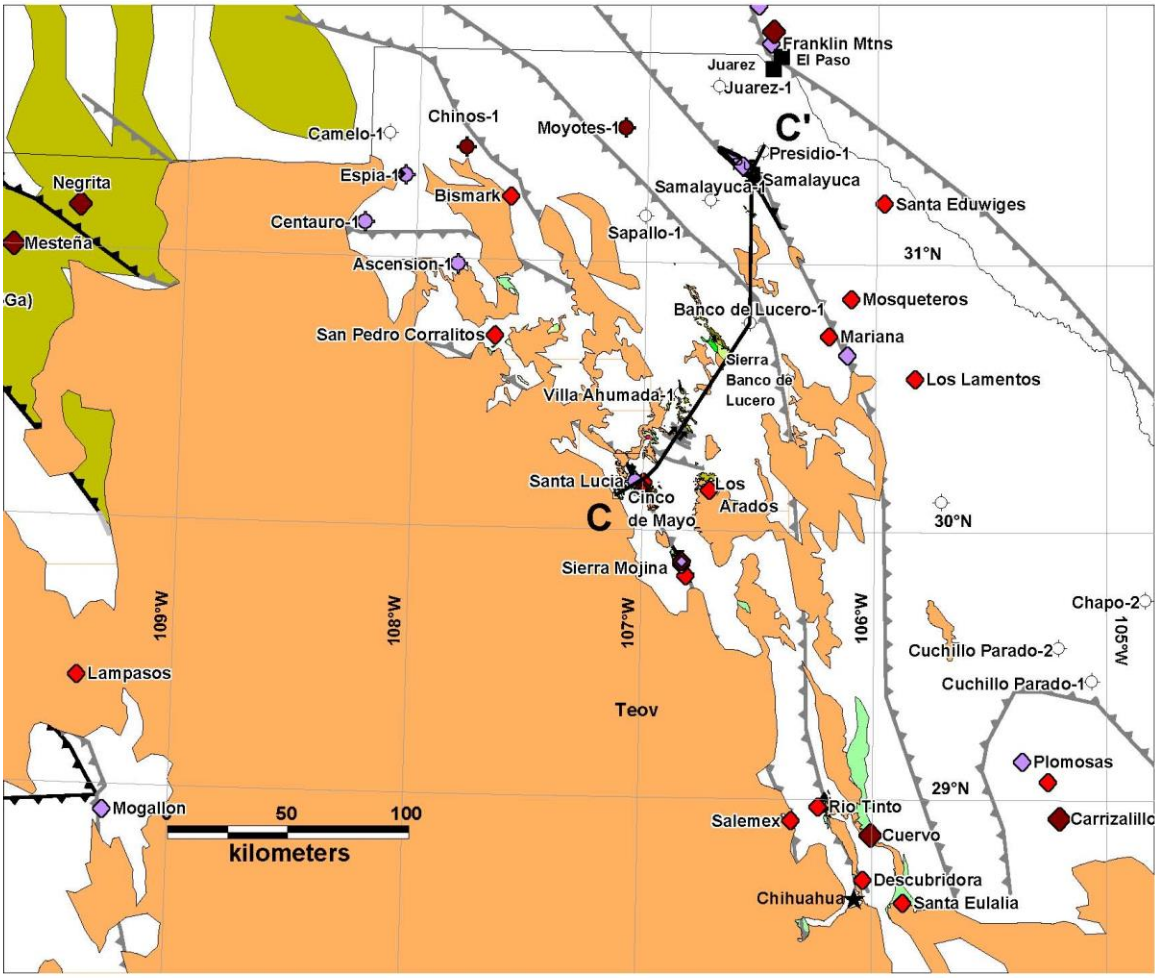

Figure 4.65 The regional setting of this study shows the Sierra Madre Volcanic Province cover for a large part of the proposed Carrizal Basin.

Windows in the volcanic cover at Sierra Santa Lucia, Sierra Mojina and Salemex help define the western margin of the Carrizal Basin. Cross section line C-C' will be the focus of this section.

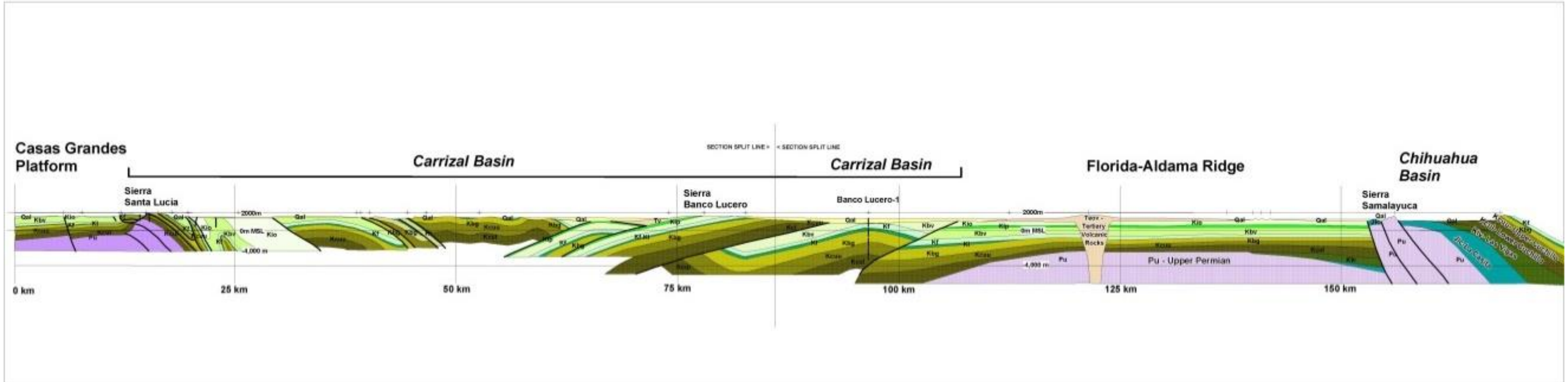

Figure 4.66 Cross section C-C' projects across the central Carrizal Basin.

The section projects from the Casas Grandes Platform in the southwest, across the Carrizal Basin, the Florida-Aldama Ridge and to the west margin of the Chihuahua Basin in the northeast (no vertical exaggeration).

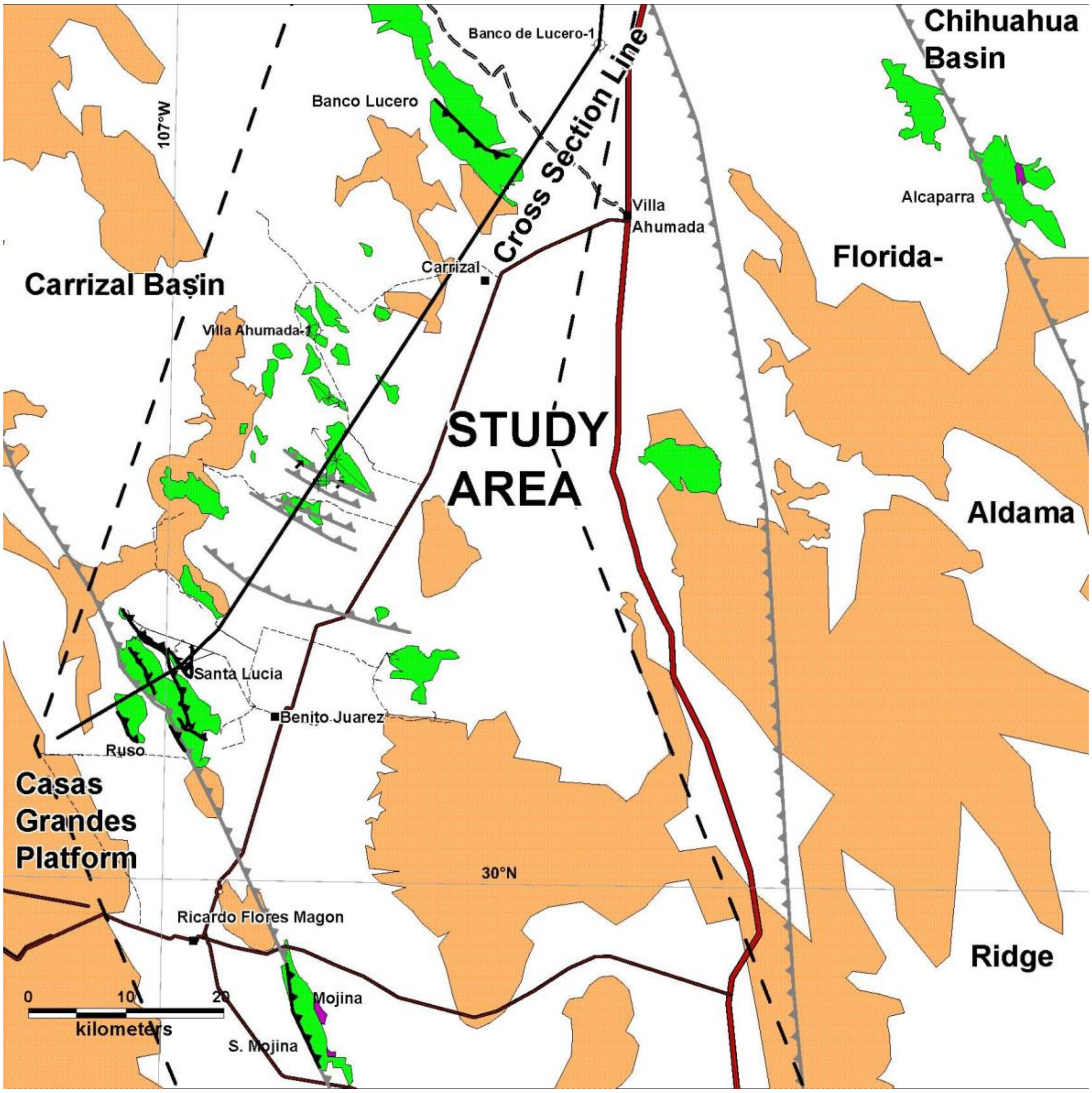

Figure 4.67 Regional geologic map of the southern half of the Carrizal Basin cross section

The central Carrizal Basin map illustrates the relationship between the various map areas (simplified in this map) and locates areas of reconnaissance mapping of Lower Cretaceous carbonates (green) with structural data. The purple units represent both published and new to this study areas of Permian strata. The brown areas represent the mostly Eocene and Oligocene intermediate to silicic volcanic rocks of the area. The gray toothed lines are estimated traces of the basin and platform boundaries that are thrusts where they are mapped in outcrop. The dashed line outlines the study area.

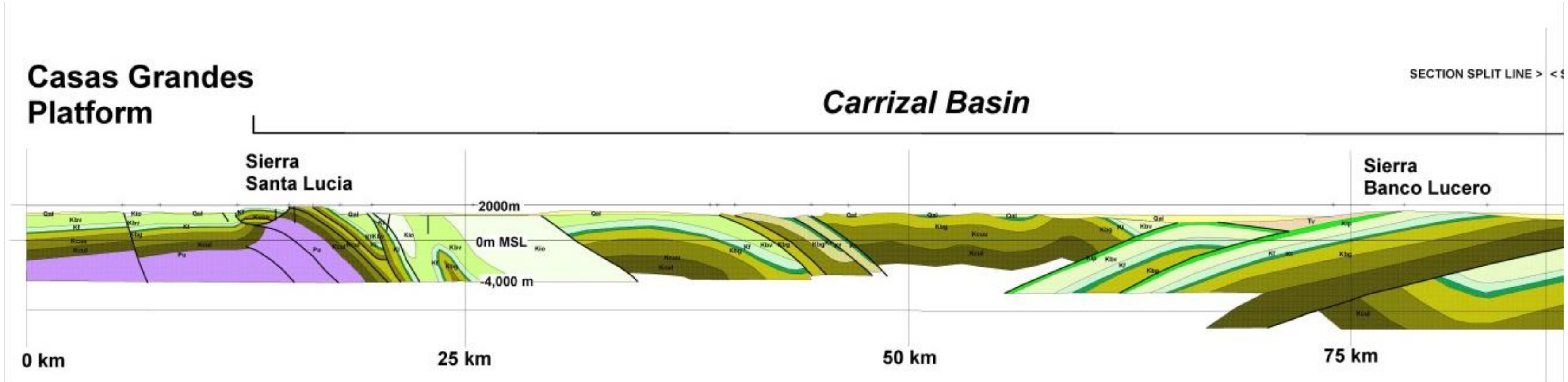

Figure 4.68 Southwest half of the cross section from the Casas Grandes Platform across Sierra Santa Lucia to Sierraa Banco Lucero.

This section shows the important characteristics of the basin with the bidirectional thrusting out of both margins of the basin and the more gentle folding in the center of the basin.

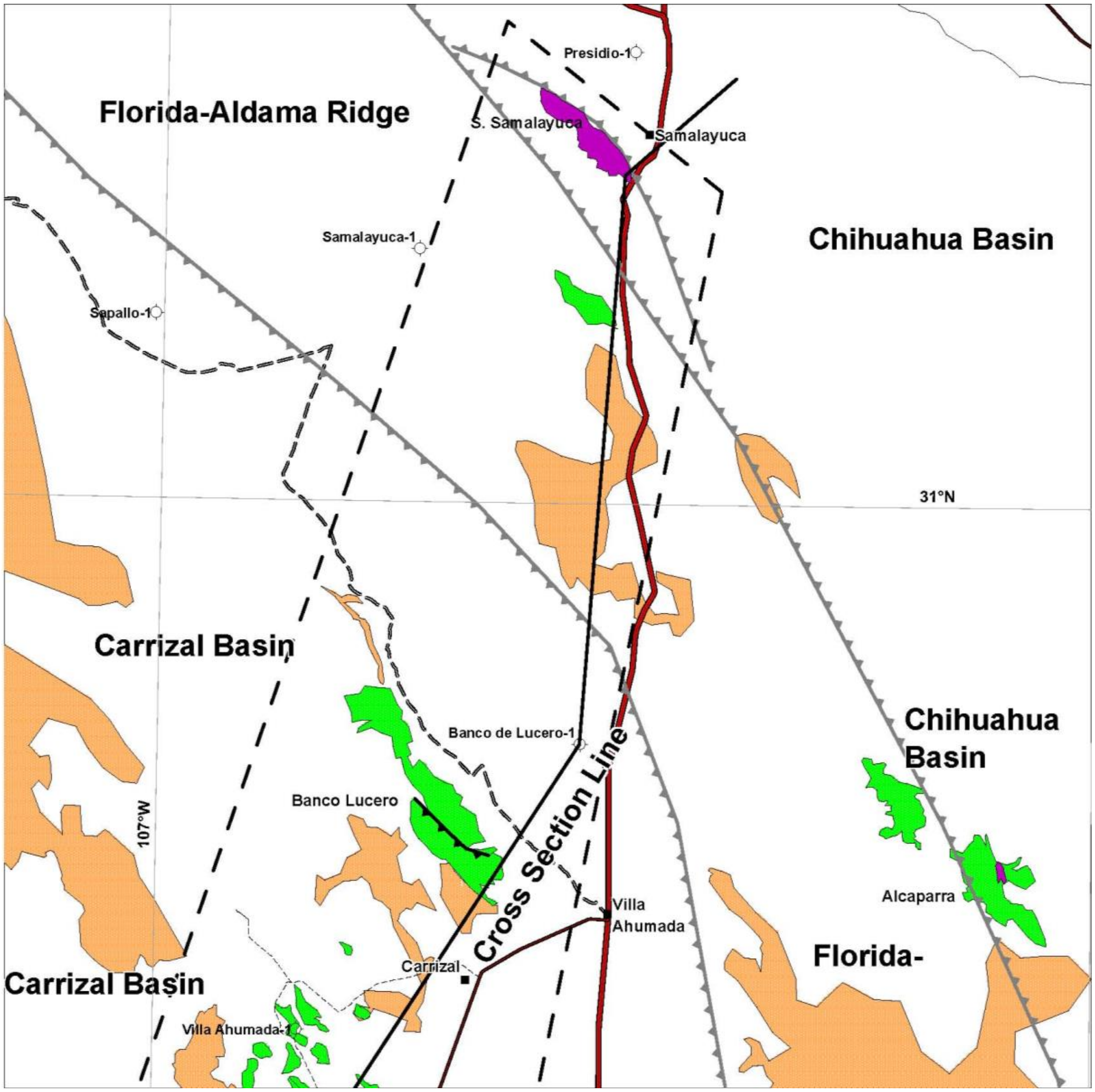

Figure 4.69 A simplified geologic map of the area between Sierra Banco Lucero and Sierra Samalayuca.

The map shows the location of weakly deformed Upper Cretaceous south of Sierra Samalayuca and the weakly deformed Lower Cretaceous carbonates of the range northwest of Sierra Alcaparra that help to define the Florida-Aldama Ridge in this area.

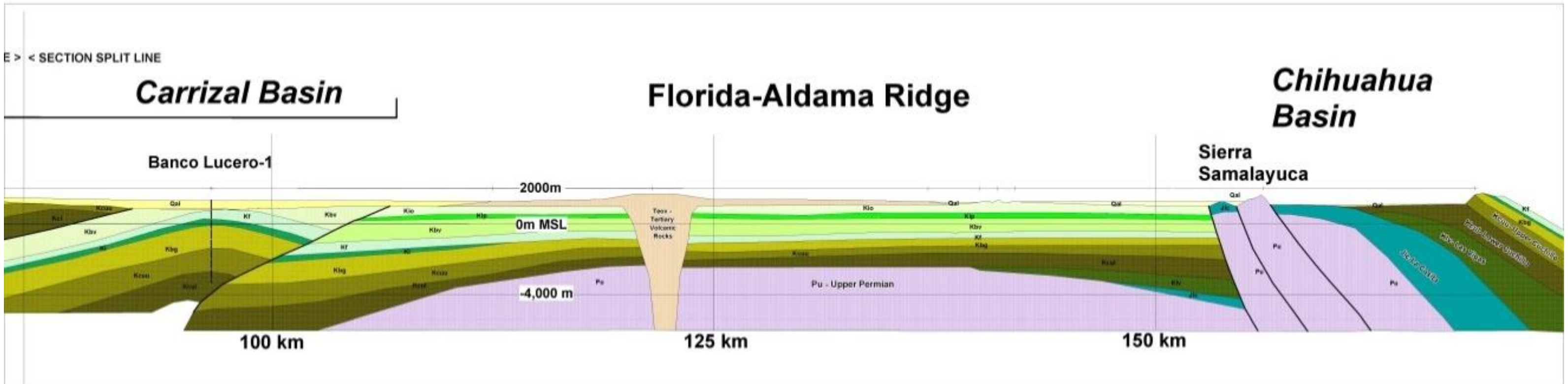

Figure 4.70 Northeast half of cross section from Sierra Banco Lucero across the Florida-Aldama Ridge to Sierra Samalayuca.

The inverted basement blocks of Sierra Samalayuca on the southwest side of the Chihuahua Basin, and Sierra Santa Lucia and Sierra Mojina on the southwest side of the Carrizal Basin suggest a pattern of these blocks forming on the side toward the driving force of shortening, the eastern Pacific subduction zone.

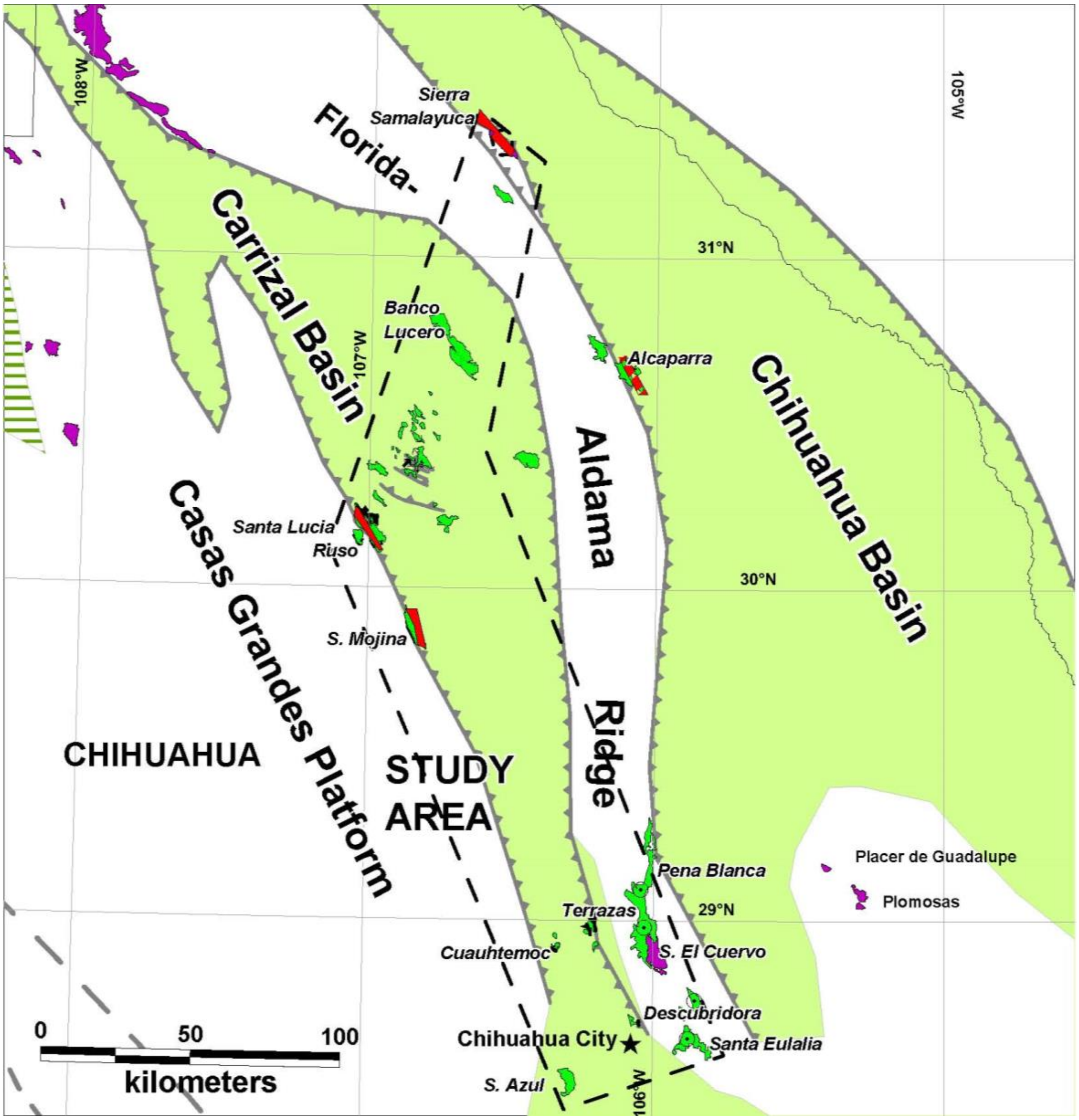

Figure 4.71 Known inverted basement blocks of north central Mexico occur along the west margins of the Jurassic intracratonic basin margins that they help define.

This observation is that they are all occurring along the west margin of their respective basins. The west side of the basin is the side where the adjacent platform is being forced into the basin during subduction induced crustal shortening whereas the on the east side the basin strata are being pushed on to the adjacent eastern platform. The inverted blocks are in red and Alcaparra is with red dashes because it is interpreted from published data and space imagery from Google Earth.

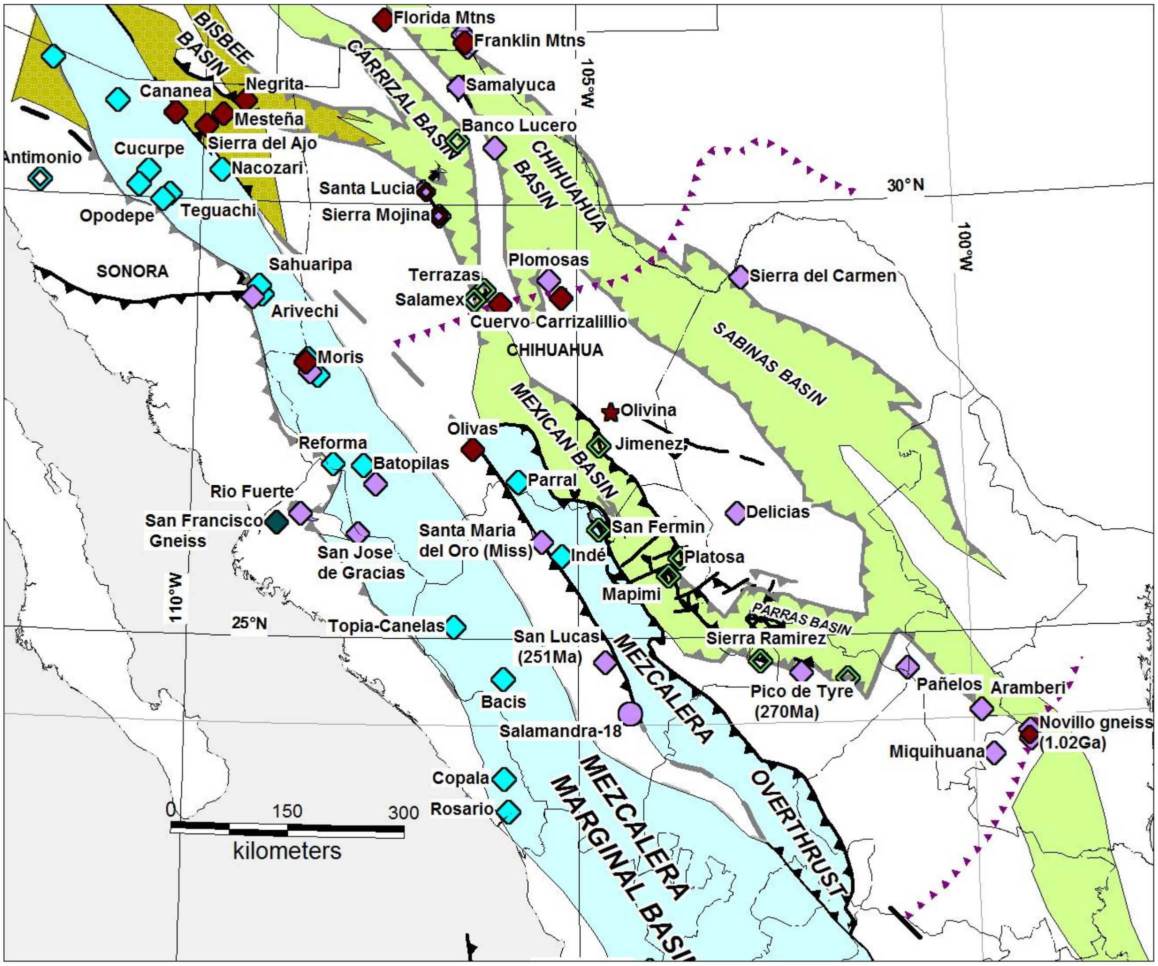

Figure 4.72 Structural definition of the intracratonic basins of northwestern Mexico.

Diamond and circle colors as before (Fig. 4.1) open green diamonds structural mapping in Lower Cretaceous limestones. Gray structures inferred and black structures mapped. Bidirectional thrusting along basin margins indicative of basin inversion.

CHAPTER 5: DISCUSSION AND CONCLUSIONS

DISCUSSION

Widely distributed reconnaissance mapping in northwestern Mexico aided by U-Pb zircon geochronology provides new insights into the Mesozoic and Early Cenozoic tectonic and volcanic evolution of western Mexico. Known Upper Jurassic deep water marine strata at Cucurpe and Arivechi, Sonora and Moris, Chihuahua and newly defined occurrences at Batopilas, Chihuahua define a coast parallel Upper Jurassic marginal basin. Basement blocks included in and protruding up through the Upper Jurassic marine strata at Cucurpe and Moris reflect an underlying extended crust produced by Late Triassic to Early Jurassic extension.

This extension created the western oceanic margin of Mexico and related extensional splits of the Mexican portion of the North American craton and the attached Late Paleozoic crust of the Ouachita-Marathon orogenic belt into a series of sub-parallel horsts and marine basin filled grabens. These grabens include the well-known but redefined Chihuahua-Sabinas Basin and the newly proposed Carrizal Basin, an extension of the redefined Mexican Basin.

The data also fill in gaps in the migration of the volcanic arc swept east and west across Mexico as the subducting oceanic plate steepened and flattened through the Mesozoic and Cenozoic Eras. This migration is well documented for the Late Cretaceous and Paleogene-Neogene (Clark and others, 1982). The new data suggests that during the time between the formation of the major Middle Jurassic Nazas arc and the Upper Cretaceous Sonora-Sinaloa Batholith the volcanic arc swept westward through the Upper Jurassic marginal basin to an offshore position forming the Alisitos Arc in the Early Cretaceous. With this continuous sweeping of the arc, accretion of oceanic arcs is unnecessary. If accumulating accreting arcs were proposed to give the appearance of westward migration, tectonic shortening should have occurred from the end of the Middle Jurassic through the Early Cretaceous rather than the extensional environment that is observed. A complex tectonic shortening event initiated at the end of the Cenomanian that has been interpreted as the collision of an oceanic arc but earlier arc accretion events have not been proposed. This is not to say no accretion occurred, but with a much less important role than accreting the whole province.

Transpressional plate migration along the west coast of North America. Clear evidence of pre-Cenomanian emplacement of the Caborca Terrane was not observed but thrusting of Caborca rocks over the Bisbee Group was documented by Mauel and others (2011).

Finally the plotting of ore deposits of Mexico over the various Mesozoic basins suggests a major influence of the distribution of these basins on the distribution of metallic ore deposits in Mexico. While complex structure along basin margins appear to be most important in forming the intracratonic basins, the presence of highly permeable clastic rocks and evaporites in the basins may have also affected this relationship. The chemistry of the oceanic basin fill and a possible basaltic component of the rifted floor of the marginal basin were proposed as possible influences on metal and trace element chemistry observed in that basin (Lyons, 2008).

Western Mexico Mezcalera Basin: A Product of Late Triassic-Jurassic Pacific Margin Extension

Contrary to the commonly accepted relationship of Mexico's intracratonic basins with the right lateral pull apart motion related to opening of the Gulf of Mexico I am proposing a divergent environment produced by plate rollback related to a Late Permian through Early Cretaceous sweeping of magmatic arc to the position of the Alisitos Arc along the western limit of Mesozoic arc migration. This divergent environment produced back arc spreading across the Mexican continent resulting in the development of the subparallel Chihuahua-Sabinas and Carrizal-Mexican intracratonic basins. A shift in the interaction between the subducting Pacific Ocean floor and the continent changed the tectonic environment to a convergent one developing the large Mezcalera Overthrust (800 by 150 km) followed by asymmetrical bivergent inversion of the intracratonic basins and an eastward sweep of the arc into west Texas. Stratigraphic correlations between Upper Jurassic outcrops suggest that the Upper Jurassic fossiliferous marine shale and turbidites interbedded with abundant andesitic tuff strata in the Cucurpe region (the Cucurpe Formation, Mauel and others, 2011) of north central Sonora were deposited in the same north-northwest-trending coast parallel continent marginal to the extensional arc basin proposed as a result of new mapping and radiometric dating at Moris and Batopilas, Chihuahua. The previously proposed Arivechi -Cucurpe seaway links Jurassic marine outcrops of the Cucurpe to Arivechi area to the Toronto-1 exploration drill hole of PEMEX in the intracratonic Mexican Basin (Haenggi and Muehlberger, 2005). PEMEX interpreted Toronto-1 as cutting Upper Jurassic La Gloria or Barriasian-Barremian Las Vigas resting on Middle Jurassic Nazas (Grajales-Nishimura and others, 1992). The platform or intracratonic basin strata reported by PEMEX poorly correlates with turbidite-rich deep marine strata observed at Cucurpe, Sahuaripa, Arivechi, Moris, and Batopilas. Also the schist observed at Valle de Olivas, Chihuahua outcrops west of Toronto-1 between the drill hole and the outcrops of Batopilas. Based on this study and the PEMEX data, the Arivechi-Cucurpe seaway appears tenuous at best.

At Batopilas, Chihuahua this mapping has delineated previously undocumented Upper Jurassic strata consisting of fossiliferous marine shale, fossil-rich turbidites and abundant andesitic domes, flows and debris locally named the Batopilas Formation. The Batopilas Formation strata are very similar to the Cucurpe Formation of Lawton and others (2003) with the exception of in place volcanic venting found at Batopilas. The observed mixing of marine strata with debris from the submarine dome at Batopilas suggests that the dominant zircon population peaking at 149Ma are probably locally sourced detrital zircons from the volcanic dome. The ammonites, although not dated, in part appear similar (T.F. Lawton, personal communication) to those dated at Cucurpe as Upper Jurassic (Villasenor and others, 2005). Corals, large nerinia and mollusks found in the Batopilas turbidite strata, while also undated; represent a fossil assemblage characteristic of the Upper Jurassic carbonate platform to the east, (Humphrey and Diaz, 2003) and were observed in detail by the author during mapping of the Jurassic Zuloaga Formation at Sierra Ramirez, Durango.

Cucurpe and Batopilas are separated by 450km but other occurrences of fossiliferous turbidite rich variably volcanic debris bearing Upper Jurassic strata at Moris, Chihuahua 150km northwest of Batopilas and Arivechi, Sonora, 250km northwest of Batopilas begin to delineate the proposed Upper Jurassic marginal basin. At Moris, Chihuahua two blocks of Precambrian gneiss capped with Paleozoic quartzite and limestone strata appear to be fragments of extended crust underlying and onlapped by the Upper Jurassic marine strata. A sandstone within marine shale on the northeast flank of the southern basement block produced a spectrum of Precambrian U-Pb ages indicating they were sourced almost entirely from the quartzite found between the gneiss and the overlying limestones. The gneiss is cut by a 1.44 Ga granite dated as part of this study.

This study has found no clear evidence of pre-Cenomanian tectonic shortening following the opening of this marginal rift basin. Northwest-trending fold and thrust axes are parallel in both the Jurassic and Lower Cretaceous but locally they appear discordant in amplitude and frequency of folding. This is believed to result from differences in rock mechanic properties. The late Cenomanian shortening as indicated by limestone and schist bearing debris flows at Salamandra, Durango, within the typically thin-bedded Indidura rests on the Mezcalera thrust sheet. The thrust sheet moved approximately 150 km to the east-northeast was then cut by the uplift of the Durango Inverted Basement Block that fed the debris flows in the Indidura. Shortening of the intracratonic basins followed the main Mezcalera thrusting as indicated by west-southwest vergent thrusting from the Mexican Basin cutting up through the Mezcalera Thrust at Atotonilco, Durango. Continuing shortening was documented by the dating of a folded rhyolite flow at Division del Norte, Chihuahua at 43.7 Ma bringing the folding into the Middle Eocene..

Thrusting of Caborca Terrane basement over the Upper Jurassic Cucurpe Formation and Lower Cretaceous Bisbee Group along the western margin of the basin and tight isoclinal folding within the Mezcalera Marginal Basin up against the North American craton margin indicate the intensity of this event. Strong folding occurs within the Bisbee Group where it overlies the Upper Jurassic marginal marine basin. No clear evidence of an older tectonic shortening event was observed during this study but has been reported in the Cucurpe region (Mauel and others, 2011). This leaves open the possibility that the shortening event correlates with the emplacement of the Caborca Terrane.

The most perplexing part of a rift origin for the Mezcalera Marginal Basin is the timing in reference to the arc migration through the area. The Permian arc is well positioned to be the initial product of subduction in the region. There is a gap in the geologic record for the Middle Triassic period in this region. Clastic strata are documented across north central Mexico during the Triassic, but evidence to link the Permian arc and the Lower Jurassic arc is weak. After the Jurassic the progress of the arc sweeping across Mexico can be tracked. It is still not exactly clear how the evidence of

Triassic rifting on the west side of the Mezcalera Basin at San Francisco and the apparent extended crustal floor to the basin are related.

Discussion of Mesozoic Arc Migration

Apparent migration of the Mexican western volcanic arc from western Mexico across to west Texas and then back during the Late Cretaceous through Miocene is well documented (Damon and others, 1981; Clark and others, 1982). Because of the cover produced by this documented arc migration, arc motion prior to this period is poorly understood. Four dates determined as a part of this study along with published work suggest that the arc migration can be traced further back at least to the Middle Jurassic and maybe as far back as Late Triassic or the Permo-Triassic magmatism in central Mexico (Torres and others, 1999). Rifting along the west coast is interpreted as having occurred in the Late Triassic based on the proposed Triassic rift origin for the Francisco Gneiss of northern Sinaloa (Keppie and others, 2006). The documented Early Jurassic rift fill in the Papago-Cucurpe rift basin (Haxel and others, 1980, 1984; Lawton and others, 2003 and Mauel and others, 2011) indicate the initial fill were continental deposits in a developing rift finally flooded by a marine incursion in the Middle Jurassic. Lower and Middle Jurassic silicic arc magmatism has been well documented from west of the Papago Basin into the Papago basin (terrane of Haxel and others, 1984) and into the Cucurpe Basin. As a result of the extensive Eocene through Miocene volcanic cover, few Jurassic occurrences are known in eastern Sonora and western Chihuahua. The belt of Middle Jurassic volcanism exposed in northwestern Sonora reappears as the well documented Nazas Formation in Durango and Zacatecas. The Mojave-Sonora Megashear (MSM) hypothesis suggests that the Middle Jurassic Nazas arc in Durango and Zacatecas was part of the northern Sonora segment of the arc and was displaced at the end of the

Middle Jurassic along the MSM to its present location in Central Mexico. The presence of the Late Triassic to Early Cretaceous Mezcalera basin cutting across the proposed trace of the MSM does not support a through going Late Jurassic MSM. The detrital zircon study of Lawton and Molina-Garza (2014) of the Nazas in the type area in north central Mexico indicates that the Nazas lacks the eolian zircons known from the northern Sonora outcrops. They interpret lack as indicating the Nazas was not transported from northwest Sonora along a transform fault such as the MSM or other proposed alternatives (Dickinson and Lawton, 2001).

There is evidence that the arc stayed relatively stationary in northern Sonora with Jurassic volcanism documented from Caborca northwest to Sasabe and eastward found at Cucurpe but migrated westward in the southern area at Moris and Batopilas, Chihuahua and Bacis, Durango. This westward migration continued through to further offshore in the Lower Cretaceous, the Alisitos Arc (Lawton and McMillan, 1999). The presence of the Alisitos arc most likely to the west was documented in this study by dating of tuffs in the Morita Formation of the Bisbee Group at Arizpe, Sonora and Zataque, Sinaloa. An apparent major realignment of plate motion along the west coast resulted in faster subduction, flattening of the subducting plate, and subsequent eastward migration of the arc. This realignment probably resulted in the relocation of the Caborca and Cortez Terranes along the proposed transpressional fault herein called the Sonora-Sinaloa Fault, the overthrusting of Caborca onto the marginal basin strata, the shortening of the marginal basin across its width and the thrusting of the basin strata on to the Upper Jurassic and Lower Cretaceous Paleozoic crust of the Central Highlands of Mexico. Starting with or following the shortening event the flattening subducting plate resulted in the eastward migration of the arc. Starting with the Tarahumara Arc and the comagmatic Sonora-Sinaloa Batholith, the arc moved slowly east to the Laramide Arc in the Latest

Cretaceous and Paleocene. In the Eocene the arc began to sweep rapidly East to west Texas before sweeping back to its final position in the Sierra Madre Occidental Volcanic Province of the Oligocene and Miocene.

This hypothesis of a more continuous sweeping of a magmatic arc to the West from the Middle Jurassic Nazas to the offshore Alisitos Arc in the Early Cretaceous represents a period of slowing subduction and oceanic plate roll-back that produced an extensional environment in the craton. The change could result from an event such as overriding of a Farallon plate related spreading ridge within the Pacific Ocean system anytime from the late Permian to the Middle Jurassic. This overridden spreading ridge would have produced much slower subduction than west of the spreading ridge and contributed to the extension observed in the Mexican craton. This extensional environment is better explains the intracratonic basins of northern Mexico and the marginal back arc rift of Mexico's northwest coast and may have been a factor in the opening of the Gulf of Mexico. A major disruption in plate motion vectors at the end of the Cenomanian resulted in transpressional motion along the coast coinciding with much faster subduction and plate flattening that produced the sweep of arc magmatism from the Lower Cretaceous Alisitos arc to Eocene-Oligocene arc in west Texas (Clark and others, 1982). This inward sweep of the arc terminated about the time that the deflection of the Hawaiian-Emperor chain at 42 Ma and began sweeping back to the west at the beginning of the Oligocene. The early Oligocene change in plate motion vectors are difficult to attribute to a particular event but would have produced a change in the direction and rate of subduction.

This hypothesis provides a much simpler model of arc development from the Late Triassic to the present than the presently accepted model of accreted oceanic arcs. If there are truly duplicate arcs they may result from the proposed transpressional motion juxtaposing several segments of the same arc. All evidence of transpression points to the same timing as proposed for arc accretion. The progression of the arcs from the Middle Jurassic volcanism through to the Eocene is illustrated in Figures 5.1.1 through 5.1.7. Data points that document or indicate the migration of the arc are shown as diamonds on Figs. 5.1.1 and 5.1.2.

Accumulating evidence suggests that the Middle Jurassic arc is probably continuous from northwestern Sonora on into northern Zacatecas (Fig. 5.1.1). The simplest explanation for the gap between the northern Sonora Mid-Jurassic volcanic field and the northwestern Durango-Zacatecas Nazas field is the cover by the Mid-Tertiary Sierra Madre Occidental Volcanic Province. Dating of outcrops of silicic volcanic breccias such as occur east of Nacori Chico, Sonora may eventually narrow this gap. How the Mid-Jurassic arc might relate to the Permo-Triassic arc is unclear but they are parallel and may indicate a steepening of the Paleo-Pacific Plate between the Permo-Triassic and the Lower Jurassic and the Middle Jurassic Nazas. As mentioned earlier a detrital zircon study (Lawton and Molina-Garza., 2014) is not supportive of the Late Middle Jurassic transport along the MSM of the Nazas from the Northern Sonora area to its present location (Jones and others, 1995).

Many models have been suggested to connect land masses of Antarctica (Borg and DePaolo, 1994), Australia (Karlstrom and others, 1999), Siberia (Sears and Price, 2000) and China (Li and others, 2002) to Laurentia in the construction of Rodinia. The problem is that they are all proposed to have been rifted in the Cambrian breakup of Rodinia or earlier. Models that address Permo-Triassic tectonics offer complex translational motion (Sedlock and others, 1993) of many small crustal fragments but no Late Triassic rift along Mexico's west coast.

Moving into the Upper Jurassic, the arc appears to pivot in north-central Sonora with the southern extent migrating into the marginal basin developing along the west coast of Mexico by further steepening of the oceanic plate (Fig. 5.1.1). As time progressed into the Lower Cretaceous, the arc appears to have migrated further off shore forming the Alisitos Arc rather than being an accreted arc (Fig. 5.1.1). This arc is assumed to be west of the study area, but tuffs of this age are documented by this study as being erupted at 124 Ma and deposited in the Morita Formation in northern Sonora and at 138Ma in Morita equivalent strata in the Sonora-Chihuahua-Sinaloa tri-state area (Fig. 5.1.1).

As we move into the Late Cretaceous the plate appears to start flattening again and the arc migrates into the Tarahumara position along with the comagmatic Sonora-Sinaloa Batholith (Fig. 5.1.2). In addition to the published documentation of the position of this arc segment (McDowell and others, 2001), U-Pb dating of zircons from various intrusive bodies and a Re-Os date on quartz-molybdenum mineralization at Batopilas as a part of this study indicate that most dikes and stocks, their hosting volcanic rocks and the associated Mo mineralization are all 90 to 85Ma. The Maastrichtian through Paleocene Laramide Arc is well documented (Figure 5.1.2) in the Cananea through Nacozari areas (cf. Barton and others, 1995) down into central Sonora (cf. McDowell and others, 2001). The well documented Eocene sweeps all the way across Mexico into West Texas (cf. Clark and others, 1982) before steepening again in the Oligocene and Miocene volcanism of the Sierra Madre Occidental Volcanic Province. The Mid to Late Miocene rifting of Baja California terminated the arc in this area with only dispersed rifting related magmatism occurring following the inception of rifting.

Mechanisms such as back arc spreading as well as arc accretion have been suggested for the basin proposed here as a marginal basin along a rifted margin. The problem with the back arc spreading mechanism is that there are no provable arcs west of the basin until the Lower Cretaceous well after the inception of deposition within the marginal basin. A Triassic arc existed to the north in California but no evidence has been found in western most Mexico other than the Sierra Los Tanques on the Sonora-Arizona border. The only dated Triassic volcanic rock in the region is the Francisco Gneiss (Keppie and others, 2006) that was interpreted as having a protolith of rift basalts.

Basin influence on Ore Distribution

Plotting the distribution of Mexican ore deposits over a map of the structurally redefined Mesozoic basin distribution reveals a strong spatial relationship between most of Mexico's sulfide ore systems and the Mesozoic basins (Fig. 5.8). This relationship has been observed in a framework of less precise distribution of the Mesozoic basins but becomes more apparent with the structural redefinition of the basins. Megaw and others (1988) proposed that the spatial relationship was with intracratonic basin margins: this study independently supports this relationship. Numerous smaller deposits occur within the basins, but most of the world class deposits appear along the margins of the basins. Mapimi, Durango originally appeared to not be on the Mexican Basin margin but remapping during this study indicates an offset in the basin margin that places Mapimi on the northeast margin of the Mexican Basin. Several mineral systems such as Santa Eulalia actually occur on the adjacent platform but always very near the basin margin. The correlation of the Mezcalera Marginal Basin with gold, molybdenum and tourmaline mineral deposits, discussed in detail by Lyons (2008), indicates that rift basalts and overlying marine shale may contribute to the localization of deposits of these elements within the Mezcalera Basin.

Presently another type of deposit presently where known occurs on the basement platforms of north central Mexico are the Oligocene volcanic eruptive related iron oxide deposits such as La Perla and Hercules, Coahuila and possibly Cerro de Mercado, Durango (Fig. 5.9). These dominantly iron oxide deposits occur within the platform areas on or near the Ouachita age basement.

The discovery of a large polymetalic deposit at the Cinco de Mayo District, Chihuahua yields strong affirmation of the model of the structural development of inverted basin margin structures as a plumbing system controlling ore emplacement. This discovery suggests the usefulness of applying this model in metals exploration. Cinco de Mayo was selected as an exploration target by Peter Megaw (Megaw and others, 1996) on the basis of small Ag-Pb-Zn vein and manto prospects very common in Mexico but these were situated in a more complex structural setting, more typical of the basin margins. The ore deposits display strong structural control ranging from the inverted basement block that defines the basin margin and the stacked thrusts that host the western Pozo Seco molybdenum deposit to the eastern thrusted Albian Finlay Limestone that contains the storm rip-up clast host bed. This host bed produced the continuity and size of the main Upper Manto ore body. The strong structural development produced an ideal crustal break to allow the emplacement of a still unobserved intrusive body that drove the hydrothermal system and produced the strong hornfels and skarn observed at depth in the core of the system.

Possible causes of the correlations of the intracratonic basin margins and sulfide deposits include structurally developed permeability along the margins both from the extension and shortening periods of deformation, higher clastic permeability within the intracratonic basins and the influence of widely dispersed evaporites in the early basins on fluid chemistry.

Tectonic Models

The presence of an apparently continuous Upper Cretaceous marginal basin with basement blocks of widely varying sizes indicates that a rifted marginal basin formed in the Early through Middle Jurassic and that its linearity is inconsistent with a major transcurrent fault (Mojave-Sonora Megashear) cutting across north central Mexico and the proposed marginal basin at about the same time. Connecting the Altar-Cucurpe Late Jurassic basin with the Mexican Sea of the craton (Haenggi and Muehlberger, 2005) is not supported by the Toronto-1 drill hole data (Grajales-Nishimura and others, 1992), but connecting the more similar deep water turbidites with interbedded volcanic strata exposed in erosional windows in the SMOVP at Arivechi, Moris and Batopilas is a reasonable alternative.

A vastly different model of Mesozoic tectonism has evolved from this study is contrary to the widely accepted models of transverse motion of the Mojave-Sonora Megashear at the end of the Middle Jurassic and arc accretion of the Guerrero Terrane in the early Late Cretaceous. The presented data suggest a rift basin accumulating continental deposits into the Middle Jurassic when it transitioned into an open oceanic marginal basin by the departure of the western margin of the rift. The marginal basin accumulated marine and submarine volcanic strata over the extended crust of the marginal basin during the Late Jurassic and as the Nazas arc migrated westward into the marginal basin. At the end of the Jurassic a large high bed load delta, the Bisbee Group flooded out of the southwestern USA into northern Sonora up till the end of the Early Cretaceous. South of the Bisbee delta, turbiditic slope and rise strata accumulated over the deeper marine strata of the Upper Jurassic. Evidence of the arc's westward migration to the position of the Lower Cretaceous Alisitos Arc is documented from distal tuffs of 136 to 124Ma found in the Neocomian strata of the Bisbee Group. Arc magmatism began migrating eastward from the Alisitos arc to the Sonora-Sinaloa Batholith in the Early Cretaceous. At the end of the Cenomanian a major change in plate motion vectors sped up subduction as indicated by the rapid eastward sweep of arc magmatism (Clark and others, 1982) and the inception of tectonic shortening and left lateral motion along the continental margin resulting in a transpressional tectonic environment. This moved the Caborca Terrane south to its present position and the toe of the Bisbee delta to the Sonora-Sinaloa-Chihuahua tri-state area. The compressive element of tectonic forces resulted in the Caborca Terrane being thrust over the Upper Jurassic through Lower Cretaceous marginal basin strata in the north (Mauel and others, 2011) and thrust the Bisbee delta toe over the similar aged turbidites and Upper Jurassic marine strata in the Sonora-Sinaloa-Chihuahua tri-state area (this study). Simultaneously the Upper Jurassic through Upper Cretaceous turbiditic strata of the marginal basin was thrust onto the continental platform strata of the central highlands of Mexico of the same age (Aranda-Garcia, 1991) confirmed in Pemex exploration drill hole Parral-1 (Grajales-Nishimura and others, 1992). Shortly after the emplacement of the thrust, large formerly extensional basement blocks along the extended edge of the marginal basin were inverted severing the link between the marginal basin and the thrust sheet converting it into a klippe. The timing of the inversion of the basement is documented in this study by the observation of limestone and schist bearing debris flows in the Latest Cenomanian-Turonian Indidura Formation in drill core and surface mapping 37 km east northeast of Durango City, Durango at the Salamandra Prospect. The limestone debris from this core contains coarse bivalve fragments that appear to most likely be rudistidae that are most common in the Albian Aurora Group.

As discussed in Chapter 4 (Fig. 4.71), asymmetry of the inverted intracratonic basins is consistent throughout the region but is most striking when plotting the inverted basement blocks. Most of these inverted blocks are found on the west-southwest to south sides of the basins. The most significant anomaly to this pattern is the Durango Inverted Basement block that separates the Mezcalera Marginal Basin from the Mexican continental crust and lies on the side away from the subducting crust.

CONCLUSIONS

The limited exposure of crystalline basement of northern Mexico has led to a variety of tectonic models. New data and reinterpreting published data have helped to create a revised reconstruction of the crust in this region. Detrital zircon data from the basal Cretaceous Las Vigas Formation of north central Chihuahua suggests the proximity of the Mazatzal basement to the area. The detrital zircon data and the lithology of conglomerate clast at Sierra Mojina indicate proximity to outcrops of the Granite-Rhyolite Province in the Early Cretaceous. Other zircons from these localities indicate regional access to Grenville and Neoproterozoic (Pan African) crust. In Coahuila, Zacatecas and Durango more localities are interpreted as Paleozoic Ouachita age crust. Despite occasional Grenville age xenoliths in volcanic vents in the Central Highlands of Mexico the degree of folding and metamorphism of the Paleozoic rocks are inconsistent with being underlain by a significant amount of older crust. This combined with the outcropping Paleozoic metamorphic basement along the west side of the Central Highlands overlain with Middle Jurassic volcanic strata suggests that the whole region is underlain by similar Paleozoic Ouachita age crust. Isolated localities of compatible Paleozoic rocks along the west coast of Mexico such as at Moris, Chihuahua could be interpreted as a belt of extended crust derived from the adjacent Ouachita age Paleozoic crust.

Published data indicate that Lower Jurassic continental strata and Middle and Upper Jurassic marine strata crop out in isolated windows in a belt along the west side of the Sierra Madre Occidental Volcanic Province from Arizona to Cucurpe, Sonora through Sahuaripa-Arivechi, Sonora and on to Moris, Chihuahua. A newly recognized occurrence at Batopilas, Chihuahua helps fill in a gap between the northern outcrops and additional known outcrops at Topia and Bacis, Durango and Copala and Rosario, Sinaloa. These Upper Jurassic strata are characterized by fossiliferous marine shale, turbidites containing carbonate shelf debris and andesitic volcanic vents and debris. It is proposed that this string of similar outcrops delineates an Early or Middle Jurassic through Early Cretaceous Mezcalera Marginal Basin. Middle Jurassic lacustrine strata mapped in the Cucurpe area and basement blocks encased in the Upper Jurassic strata at Moris along with evidence that the arc is moving westward suggests that the marginal basin was created by extension in the Middle Jurassic during which it was filled with continental deposits and mafic flows (Rancho San Martin Formation) followed by a Middle to Upper Jurassic marine incursion (Lily, Cucurpe and Batopilas Formations).

Lower Cretaceous deposition consisted of alluvial fans to a high-bed load, reworked delta complex of the Bisbee group in northern Sonora, to thin bedded calcareous shelf deposits from northwest of Batopilas, Chihuahua to south of Chirimoyo, Durango. The Bisbee Group's reworked delta complex is divided by an Aptian-Albian marine incursion that produced the reef and lagoon strata of the Mural Formation throughout the basin.

A belt of Ouachita-age Paleozoic metamorphic rocks, referred to as the Tesoro Formation of the Parral Terrane in the literature, separates the marginal basin from the Mezcalera overthrust of these same basin strata emplaced onto the craton in the Late Cenomanian. The so-called Parral Terrane is here interpreted as an inverted basement block of Ouachita age crust underlying Mexico's Central Highland that was uplifted by continued shortening following the initial overthrust. The large block of variably metamorphosed Paleozoic strata, the Rio Fuerte Formation, found from southwest of Choix, Sinaloa across to Diego de Gracias is interpreted as a block of extended crust of central Mexico's Paleozoic crust.

The largest best studied outcrop of the basin fill is in the Cucurpe area in north central Sonora. Folding and thrusting occurs in the Upper Jurassic through Lower Cretaceous up into the Cenomanian strata from Cananea, Sonora to the Santa Ana area west of Cucurpe. Precambrian in the Cucurpe area appear to consist of rafted blocks in the Jurassic strata and post Albian overthrusting from the Caborca Terrane. At Moris, Chihuahua the upper Jurassic marine strata are found encasing isolated blocks of Precambrian gneiss through Paleozoic supracrustal basement. The presence of these blocks during deposition of the marine strata is indicated by detrital zircons in sandstones along the flanks of the basement blocks only yielding Archean and Proterozoic zircons assumed derived from the basal quartzite in the adjacent basement block. At Batopilas, Chihuahua, submarine andesitic volcanism dated 149Ma is interlayered with fossiliferous strata and turbidites. The Upper Jurassic strata are overlain by Upper Cretaceous andesite flows that are cut by stocks dated at 88 to 85Ma. This age indicates the andesite flows are Upper Cretaceous Tarahumara Formation equivalent.

The distribution of the Upper Jurassic rise through Lower Cretaceous shelf strata along the paleo-Pacific coast of northwest Mexico and its probable continuation into southwest Mexico suggest that a marginal basin existed in the present location of the previously proposed Guerrero Terrane.

Close in time to the Late Triassic-Early Jurassic extension along the west coast, extension also broke up the crust of the interior of the Mexican craton creating the intracratonic basins of the interior of Mexico sub-parallel to the marginal basin. The proposed development of these intracratonic basins in association with the rifting of the Gulf of Mexico basin is somewhat awkward since the extensional vectors are perpendicular. These intracratonic basins were originally delineated by facies analysis and various models have been proposed for the structural evolution of the associated fold belts. Proposed models included tilting produced detachment surfaces controlled by evaporite horizons and basin inversion. Regional reconnaissance mapping and more detailed mapping in widely scattered mineral districts defines basin inversion produced by shortening across the basins as the driving mechanism for fold belt formation in northern Mexico. Each basin is defined by bidirectional thrusting out of each opposing margin with folding being the main shortening result within the basin. Inverted basement blocks are found along the subduction side of the intracratonic basins, but a major inverted basement block, the Durango Basement Block, is located along the cratonic side of the marginal basin. Building on the work of Haenggi (2000), it was determined that his definition of the Chihuahua Trough was overly broad and was actually two parallel basins separated by a ridge that had been defined as the Aldama Platform. As there was a new basin now referred to as the Carrizal Basin separating Aldama from a larger platform to the west, the western platform has been named the Casas Grandes Platform. The ridge is named for the outcropping basement elements along it the Burro-Florida-Aldama Ridge. Because of volcanic cover, it has not been determined with certainty that there are no other basins within the Casas Grandes Platform or exactly how the Carrizal and Chihuahua Basins might or might not connect with the Mexican Basin to the south. The Mexican basin continues south to the Torreon area where it turns east along the south side of the Coahuila Platform. The Parras Basin is a younger, smaller parallel foreland basin superimposed over the Mexican Basin along the south side of the Coahuila Platform. The bidirectional thrusting out of the Mexican Basin mapped between Parral and Mapimi continues around the easterly deflection of the basin where it is well documented at Sierra Ramirez on the south side and in Pemex drill holes on the north side of the Mexican Basin.

A model of the sweeping of the magmatic arc from the Lower to Middle Jurassic Nazas Arc through the marginal basin strata is documented by the Upper Jurassic Arc volcanism dated 149 Ma at Batopilas and follows on to its westernmost position the Lower Cretaceous Alisitos Arc. Accretion of oceanic debris of sea mounts and spreading ridge deposits at the subducting margin throughout its history, explains much of the complex oceanic features observed in the Guerrero Terrane.

A major Late Cenomanian tectonic event such as a change in the angle of motion of the subducted plate or the subduction of a spreading ridge produced translational motion along the coast with a greatly increased subduction rate and greater compressive stress in Western Mexico. This transpressional event probably accounts for the emplacement of the Caborca Terrane and truncation of the leading edge of the Bisbee Group and translation 600km south to its present position in the Sonora-Chihuahua-Sinaloa tri-state area. It could have also produced stacked arc segments observed in southwestern Mexico. The greater subduction rate flattened the angle of slab subduction and produced an eastward sweep of the arc into the craton from the Turonian to the Early Eocene. The arc moved into the position of the early Late Cretaceous Tarahumara Arc with its comagmatic Sonora-Sinaloa Batholith then migrated further east to form the Maastrichtian-Paleocene Laramide arc found on the east side of the Sonora-Sinaloa batholith. Starting with the Eocene the arc swept rapidly east to West Texas and then back to the position of the Oligocene-Miocene Sierra Madre Occidental Volcanic Province. Except for the accretion of sporadic oceanic debris the so called Guerrero Terrane appears to be an in place marginal basin with some transpressional dislocation. If this is the case the region would more correctly be referred to as the Guerrero Province or to avoid confusion between the various models the Mezcalera Province.

The tectonic shortening of this marginal basin can only be well documented as a major Late Cenomanian tectonic event. Thrusting of the Caborca and Cortez Terranes over the Upper Jurassic and Lower Cretaceous basin strata occurred in the Cenomanian as did the thrusting of the Mezcalera Thrust on to the Central Mexican Platform as indicated in Pemex drill hole Parral-1. Uplift of the Durango inverted basement block followed as did the tectonic shortening of the intracratonic basins now documented to have continued into the Late Eocene by folded Eocene volcanic strata.

The location of most metallic mineralization of western and central Mexico can now be shown to be principally controlled by structural features along the margins of the intracratonic basins first produced by basin extension and then reactivated by basin inversion of strata deposited across the basin margin by tectonic shortening across the basins. Clastic strata permeability and chemistry of the evaporitic and marine shale strata found in the basins may have further influenced mineral district formation. These relationships are compatible with results of minerals exploration at Cinco de Mayo. Stocks with significant magnetite and associated aeromagnetic anomaly were observed east of Parral, Chihuahua that cut across the boundary between the Coahuila Platform and the Mexican Basin. In the Mexican Basin the stock lost its magnetic signature and pyrite was observed in the stock instead of magnetite. Additional studies of such aspects as indicated sources from S isotopes might provide further support for the possible influence of basin chemistry and nature of the resulting mineral deposits.

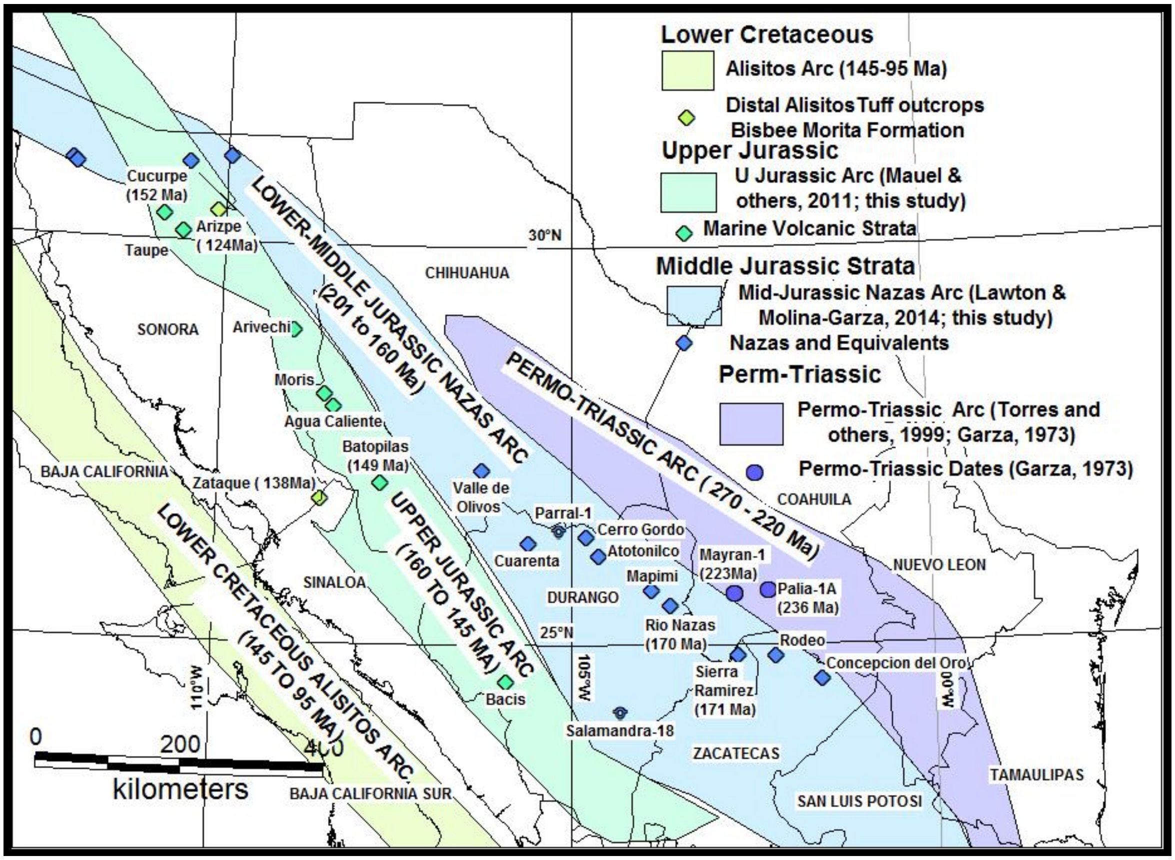

Figure 5.1 Arc migration from the Permo-Triassic through the Early Cretaceous as revised by this study.

The field of Lower to Middle Jurassic Nazas arc rocks has been expanded southwest by newly recognized occurrences at Salamandra, San Lucas and Indé. The position of the Upper Jurassic is newly determined using U-Pb ages on detrital zircons at Cucurpe (152 Ma, Mauel and others, 2011) and at Batopilas (149 Ma, this study). Although the Early Cretaceous Alisitos Arc is west of the study area (Baja California), U-Pb ages from 2 localities of distal tuffs below Mural Limestone equivalent outcrops (124 Ma at Arizpe and 138 Ma at Zataque, both from this study) indicate presence of the Alisitos Arc.

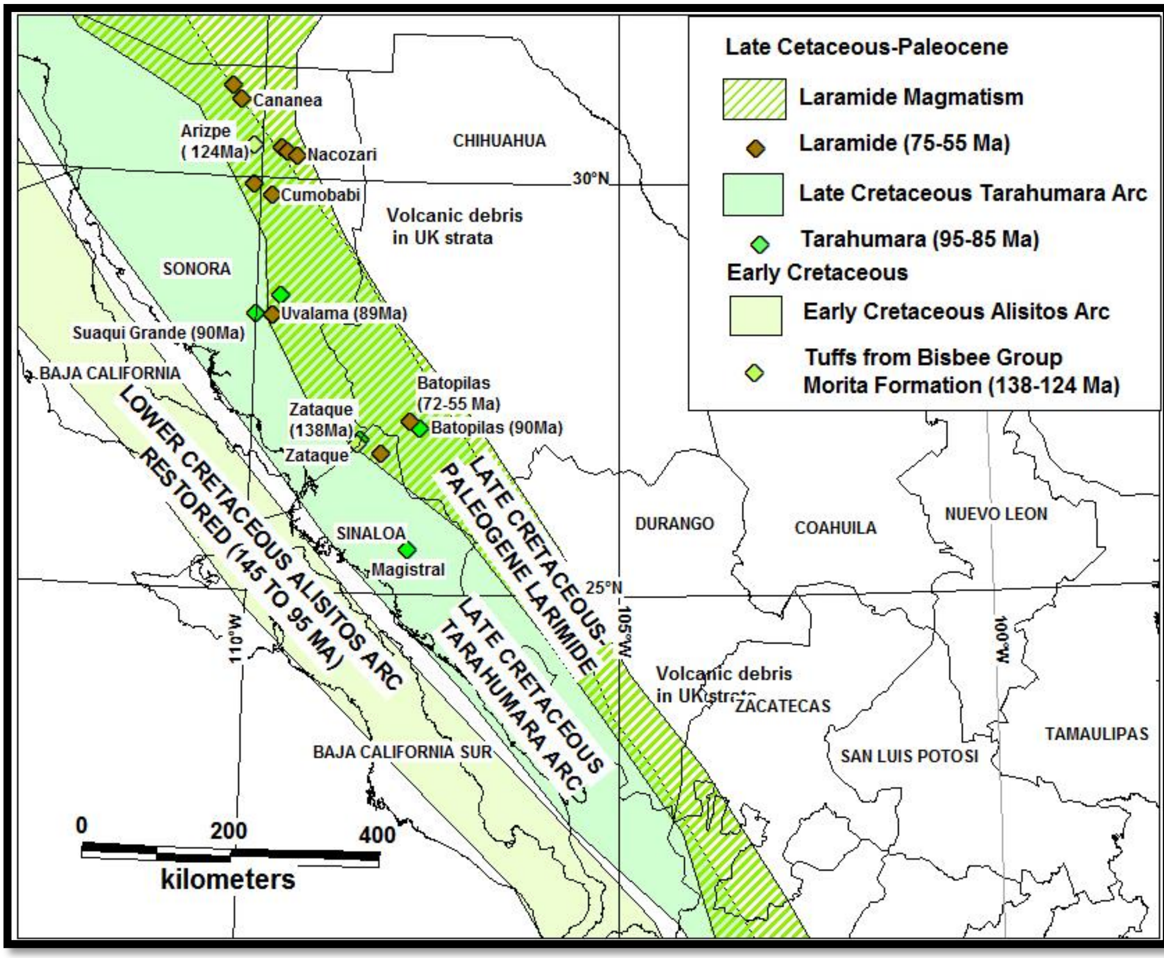

Figure 5.2 The arc sweeps back to the east from the Early Cretaceous Alisitos Arc, through the Late Cretaceous Tarahumara Arc to the Late Cretaceous-Paleogene Laramide Arc.

U-Pb ages from Suaqui Grande (McDowell and others, 2001) yielded both Tarahumara ages (90 Ma) for volcanic rocks and Laramide ages (70 Ma). U-Pb ages on the comagmatic stocks that cut the subaerial volcanic rocks at Batopilas indicated Tarahumara age (85 to 88 Ma).

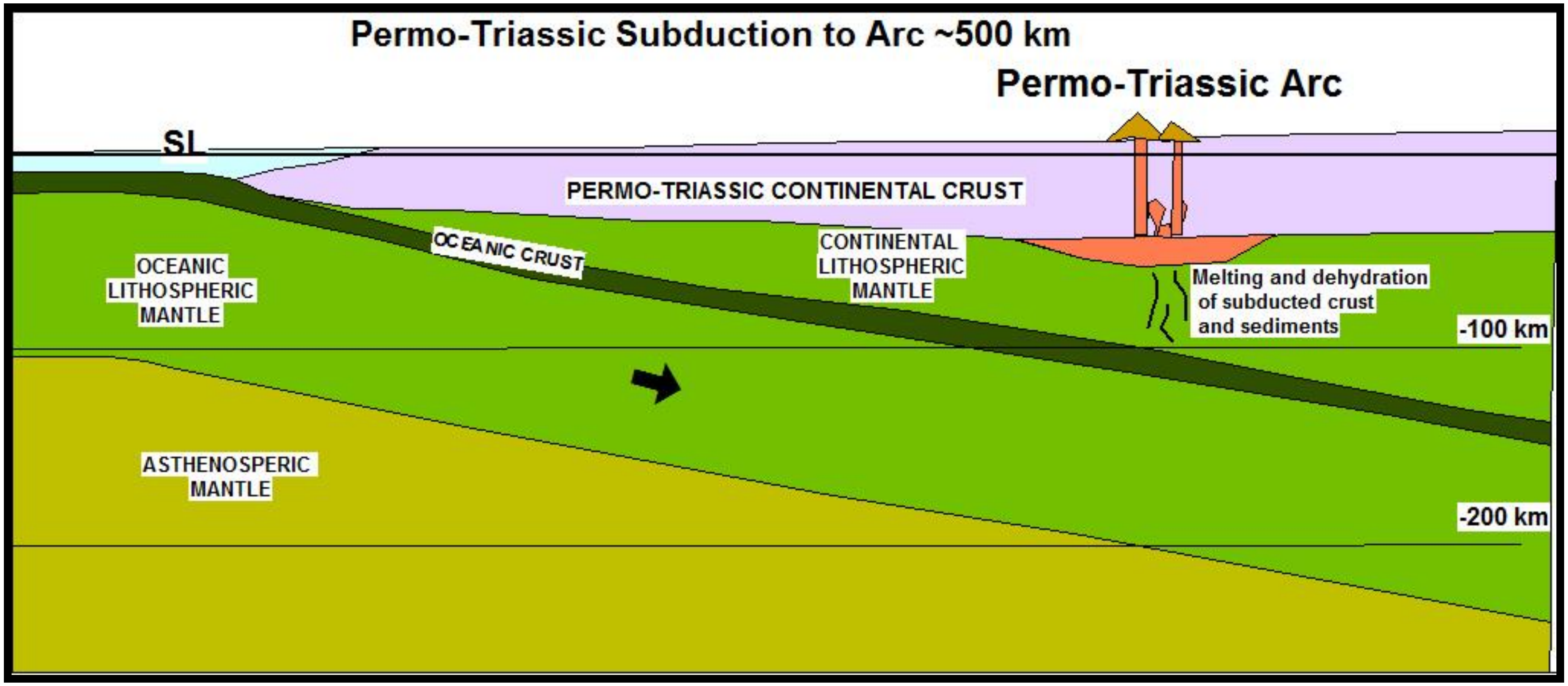

Figure 5.3 After the suturing of Gondwana to North America (~280 Ma), rapid subduction developed along the Pacific margin from 270 Ma to 220 Ma.

This subduction appears to have produced a low angle (~-10°) oceanic crustal subducting plate as indicated by the large distance of the arc from the subducting oceanic plate.

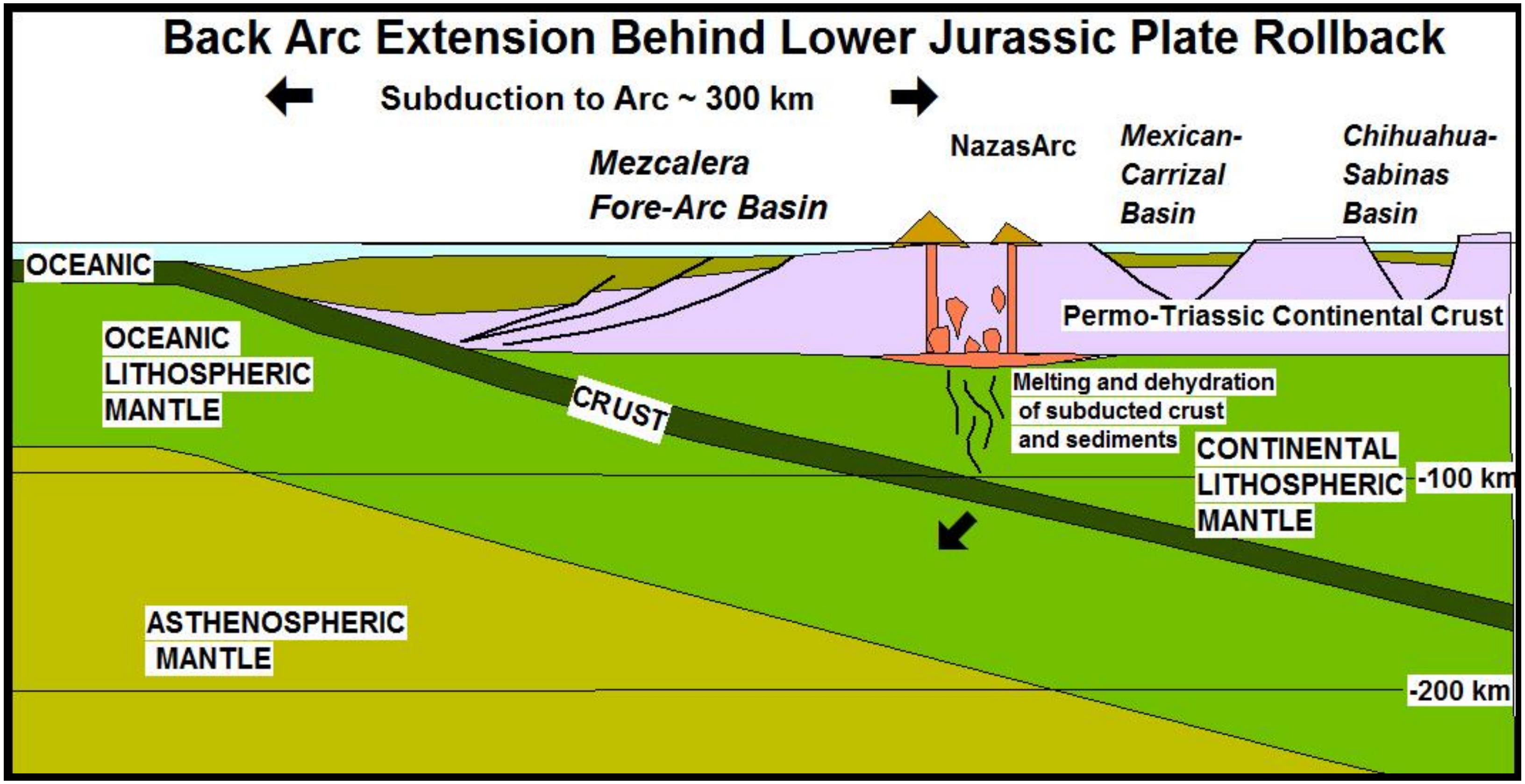

Figure 5.4 Illustration of the extensional environment produced by oceanic slab rollback during the Nazas Arc eruption (190-165 Ma, Lawton and Molina-Garza, 2014; this study).

Rising infilling asthenosphere behind the plate adds to the extensional environment. During the Early through Middle Jurassic the extensional period the intracratonic extensional basins form behind the arc . The Mezcalera Basin is a forearc basin accumulating turbidites in a deep water rise environment

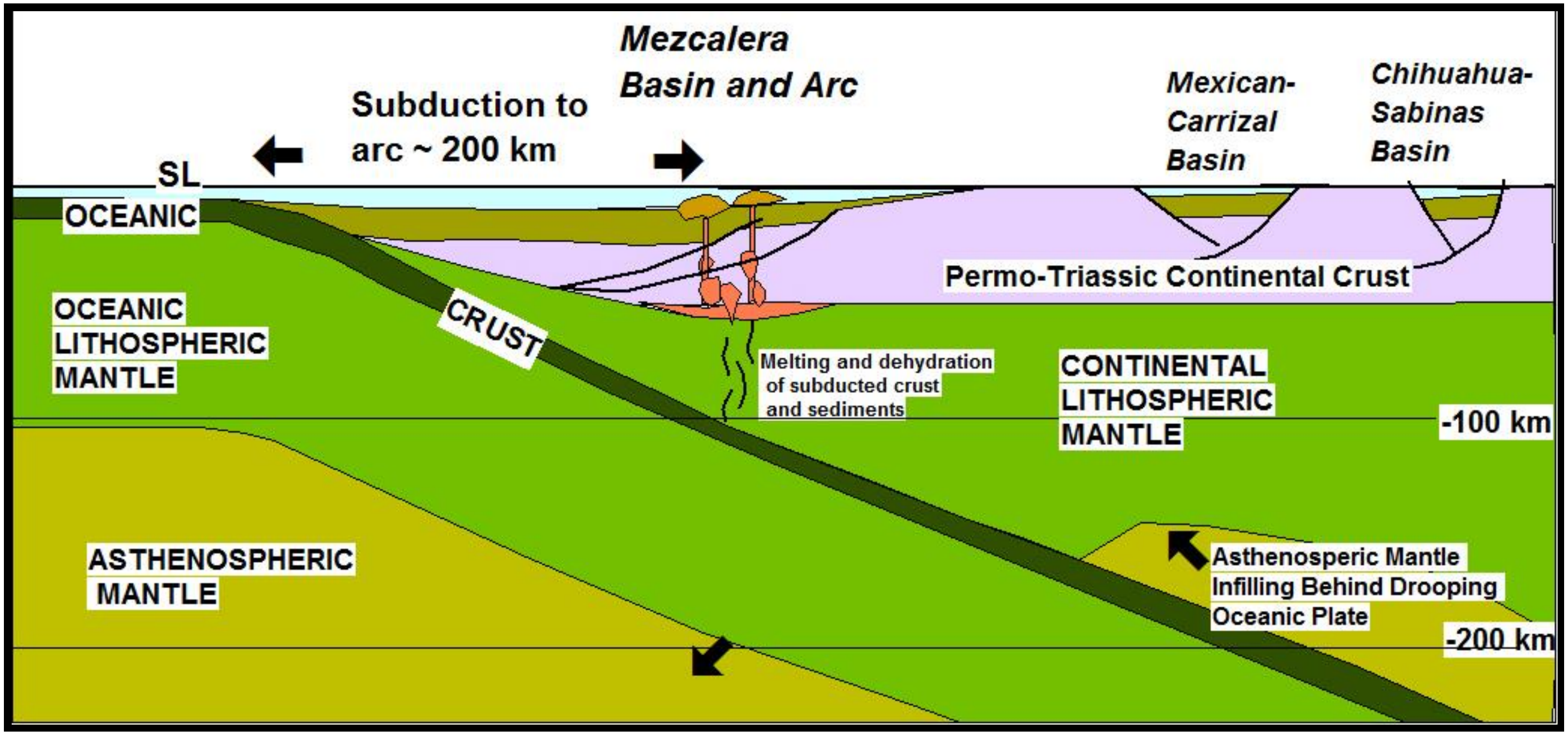

Figure 5.5 Arc continues its westward migration during the Upper Jurassic (160-145 Ma) changing the Mezcalera to an intra-arc basin with concurrent volcanism.

Arc migration and extension occur behind Late Jurassic plate rollback.

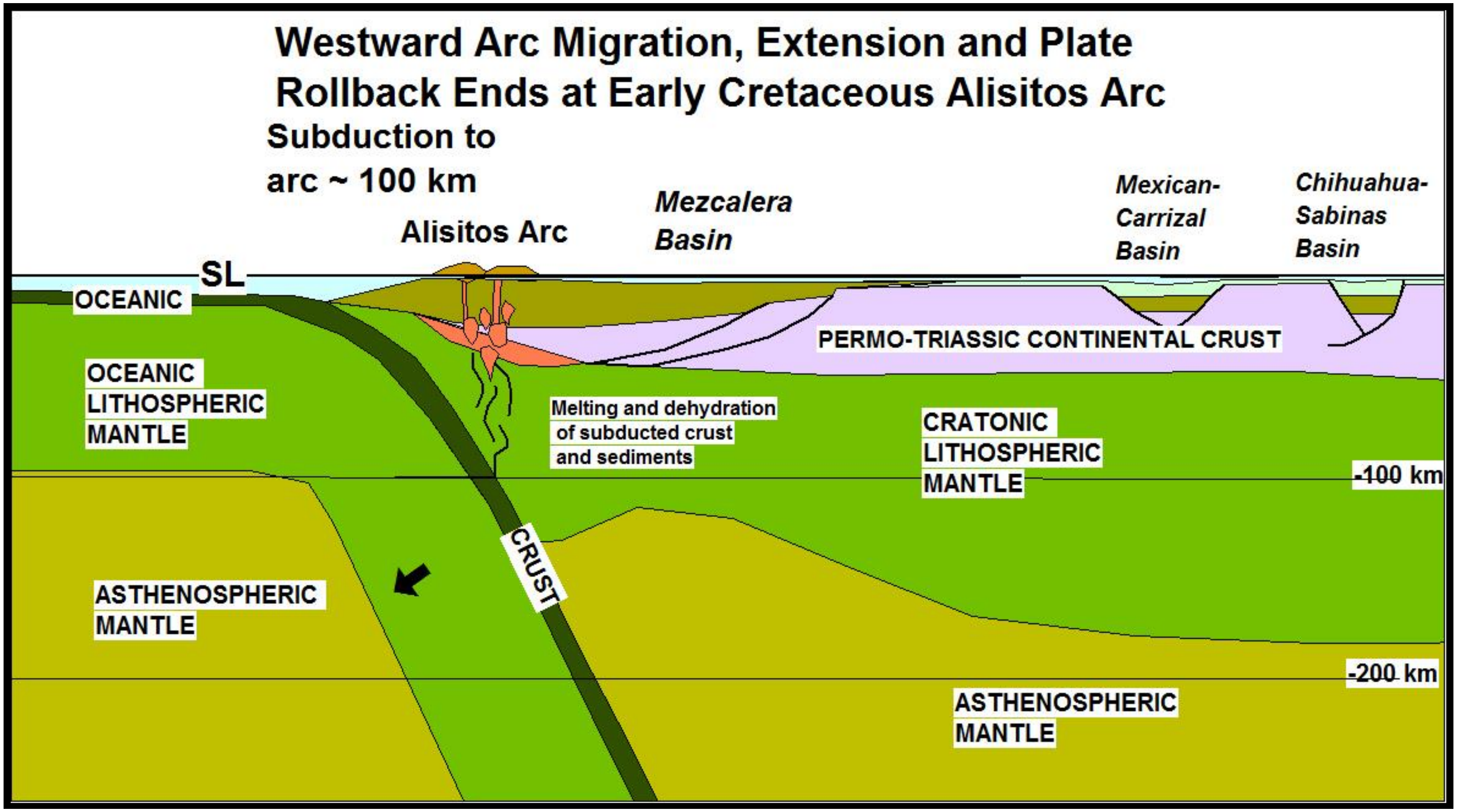

Figure 5.6 The Alisitos Arc (138 to 124 Ma this study) represents the culmination of the westward Mesozoic arc migration and intracratonic extensional basins.

The arc is at its closest point to the subduction zone. The Mezcalera Basin is accumulating deep shelf deposits as observed in this study at Gochic, Sonora and Chiramoyo, Durango.

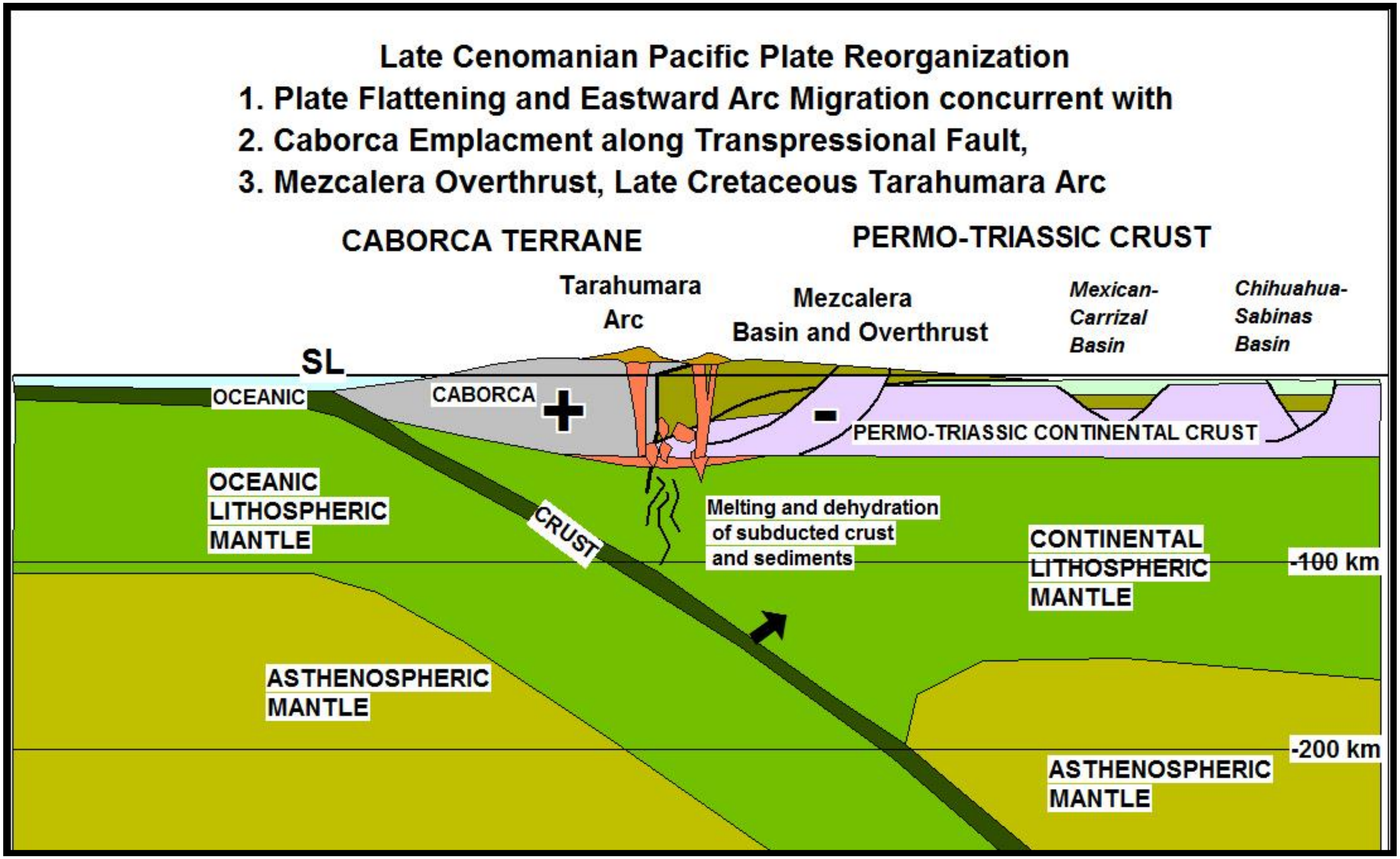
Late Cenomanian Pacific Plate Reorganization
1. Plate Flattening and Eastward Arc Migration concurrent with
2. Caborca Emplacment along Transpressional Fault,
3. Mezcalera Overthrust, Late Cretaceous Tarahumara Arc
CABORCA TERRANE
PERMO-TRIASSIC CRUST
Tarahumara Arc
Mezcalera Basin and Overthrust
Mexican-Carrizal Basin
Chihuahua-Sabinas Basin
SL
OCEANIC
CABORCA
+
-
PERMO-TRIASSIC CONTINENTAL CRUST
OCEANIC LITHOSPHERIC MANTLE
CRUST
Melting and dehydration of subducted crust and sediments
CONTINENTAL LITHOSPHERIC MANTLE
-100 km
ASTHENOSPHERIC MANTLE
-200 km
ASTHENOSPHERIC MANTLE

Figure 5.7

Figure 5.7 A major realignment of plate motion at the end of the Cenomanian brought intense transpressional forces to the region.

The forces produced two vectors of motion, one an increased rate of subduction resulting in eastward arc migration to the position of the Tarahumara Arc (Sonora-Sinaloa Batholith 95-80 Ma) along the present west coast of Mexico and the coast parallel vector moving Caborca and associated terranes out of the western U.S.A and down the west coast of Mexico. The compressive forces resulted in Caborca being partially thrust over the Mezcalera strata and eastern strata of the basin being thrust onto the Paleozoic portion of the adjacent crust. Continued shortening uplifted basement producing inverted basement blocks both along the eastern side of the Mezcalera Basin and the western sides of the intracratonic basins.

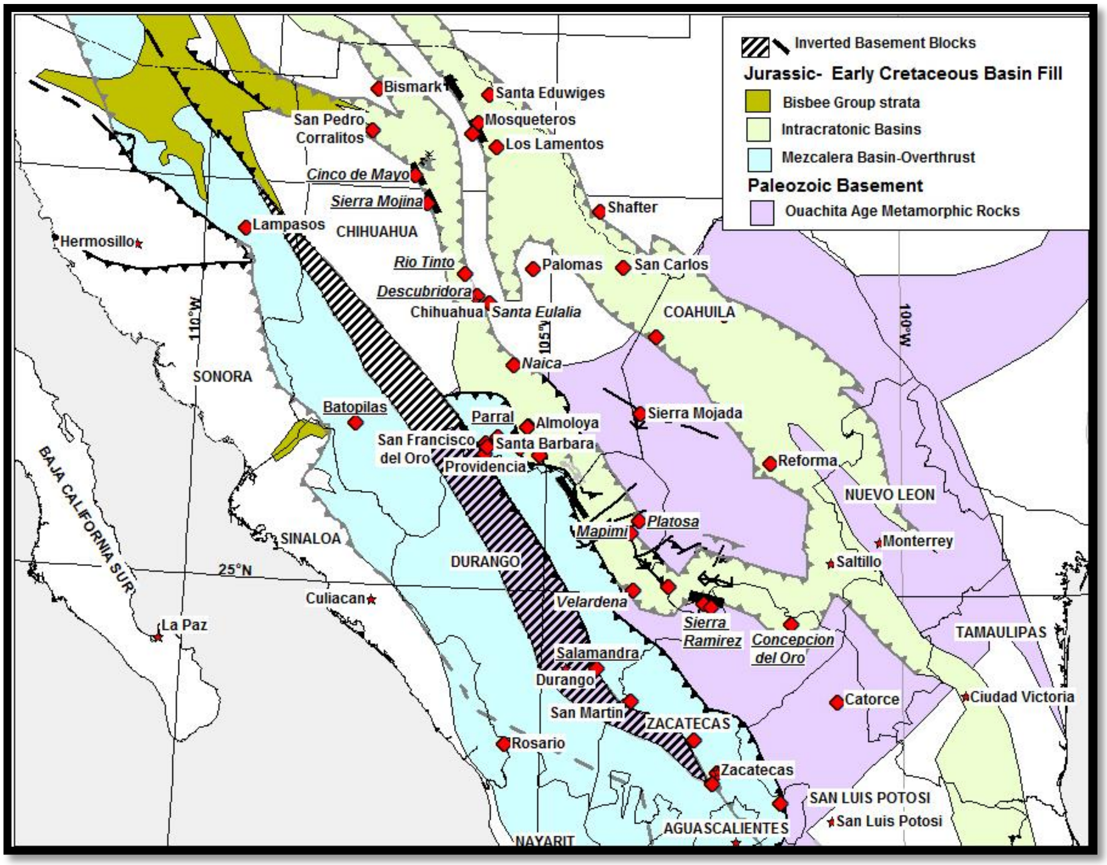

Figure 5.8 Carbonate replacement deposits of northern Mexico (red diamonds) display a strong correlation with the structural margins of the intracratonic basins.

The structurally complex margins of the basins appear to develop favorable ground preparation for the movement of hydrothermal fluids.

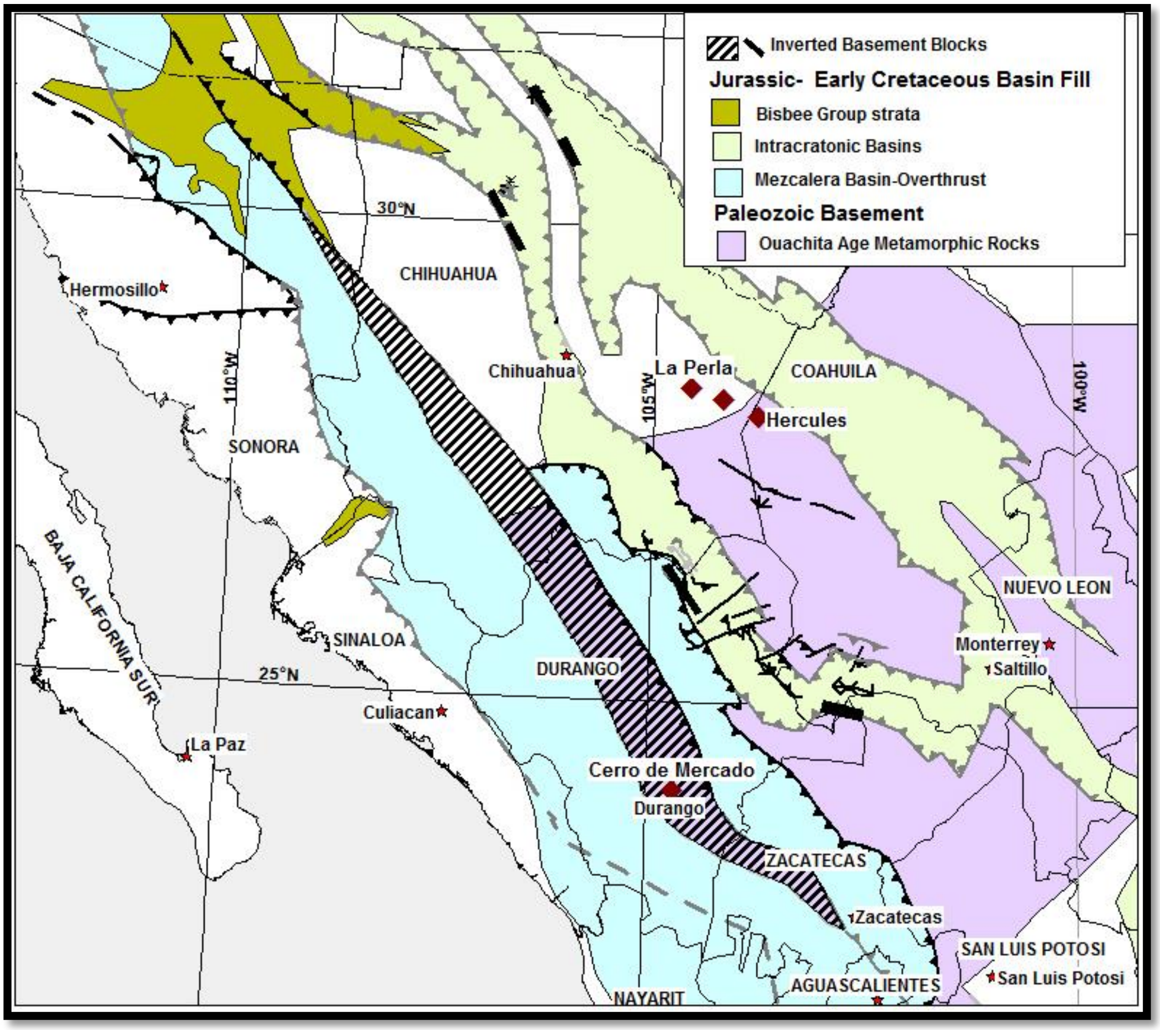

Figure 5.9 The iron oxide deposits associated with the Oligocene volcanism of north central Mexico (Fe deposits Tuscan red diamonds..

The iron deposits display an association with the Ouachita age Paleozoic basement especially when considering the uncertainty of the boundary of Laurentia and Ouachita age basement. This relationship was strengthened with the recent discovery of Paleozoic schist just east of Ciudad Durango.

Appendices

APPENDIX A: RADIOMETRIC DATING OF ROCKS FROM THE STUDY AREA (DATA INCLUDED IN ATTACH SUPPLEMENTARY FILES)

Introduction

Dating of zircons from Precambrian to Tertiary rocks was carried out to aid in correlations of units and understand provenance of the units. The original intent was to follow the practice of Lawton and his students (Mauel and others, 2011) in their provenance studies of the Cucurpe Basin in northern Sonora. In practice more volcanic tuff-rich units were sampled yielding more actual ages than provenance results.

The principal analytical technique used in this study has been from U-Pb determinations from zircons in igneous rocks and detrital zircons from 2 separate collections. Both batches were processed by Victor A. Valencia, the first at the University of Arizona Geosciences Geochronology Center by laser-ablation ICP mass spectrometry and the second batch at Washington State University by the same technique. One Re-Os date on the molybdenite mineralization in a quartz vein cutting a quartz monzonite dike in the footwall of the Todos Santos vein at Batopilas was also run at the University of Arizona.

Zircon U-Pb ICP-MS laser Geochronology

Around ~5-10 kg of each sample were processed for zircon extraction using standard heavy liquid and magnetic separation methods at the University of Arizona and ZirChron LLC. A large fraction of the recovered zircons were mounted in epoxy resin and polished. Selection of detrital zircons for analysis was made at random from ~100 of the zircons mounted. Cores of grains were preferentialy analyzed to avoid possible metamorphic overgrowth or lead loss. For magmatic samples ~35 analyses were performed, analyzing tips and cores.

U-Pb geochronology was conducted at the University of Arizona (U of A) and Washington State University (WSU). Operating procedures and parameters are described in Gehrels and others, (2008) and Chang and others, (2006), respectively.

Zircon crystals were analyzed after CL imaging using 1” polished epoxy grain mounts with a Micromass Isoprobe multicollector ICP-MS equipped with nine Faraday collectors, an axial Daly collector, and four ion-counting channels coupled to a with an ArF Excimer laser ablation system with an emission wavelength of 193 nm (U of A) and a ThermoFinnigan Element 2 single collector, double-focusing, magnetic sector ICP-MS coupled to a New Wave Nd: YAG UV 213-nm laser (WSU). Laser spot size and repetition rate were 35 microns and 8 Hz (U of A), and 30 microns and 10 Hz (WSU). He and Ar carrier gases delivered the sample aerosol to the plasma. U-Pb diagrams were plotted using Isoplot 3.0 (Ludwig, 2003). U-Pb zircon crystallization ages errors are reported using quadratic sum of the weighted mean error plus the total systematic error for the set of analyses (Valencia et al. 2005). Spreadsheets with all of the results and images of dated zircons are presented in the Supplemental Files.

Precambrian

The northern outcrop of the two basement blocks mapped north of Moris, Chihuahua was sampled at two localities, one a granitic plug and the other a gneiss forming the host of the granite. The granite dated at 1,442.6Ma ±17.6Ma from 29 zircons and the gneiss has not yet been dated. The date on the granite indicates the gneiss is likely of Mazatzal (1.65Ga) or earlier Proterozoic age.

A date from the shale-sandstone unit on the side of the southern basement knob yielded only Precambrian zircon ages. The majority of both samples are Archean age zircons (2.5 through 2.9 Ga) with Yavapai through Mojave (1.7 through 2.0 Ga) and a minor cluster of Grenville age zircons (1.1 Ga). The suite of zircons found in the sandstone are interpreted as being an unlikely suite to derive from the basement gneiss therefore most likely has been derived from transported zircons from the quartzite at the base of the Paleozoic section that caps the underlying basement block.

Mezcalera Group -Batopilas Formation

The only successful attempt at dating the Upper Jurassic marginal basin was at Batopilas, Chihuahua in the Roncesvalles Member of the Batopilas Formation. Sample JL-B-02 came from an outcrop of volcanic ash-rich, belemnite fragment-bearing shale between the Animas Andesitic Dome Member and the Minas Andesite Breccia Member east of the Pastrana Mine. The zircons yielded a U-Pb date of 149Ma that included 85% of the zircons (data in Appendix) that is essentially identical to the date acquired by Mauel and others (2011) from the Cucurpe Formation in northern Sonora. The zircons also included 2 Archean zircons, 5 Paleoproterozoic, 2 Mesoproterozoic of Granite-Rhyolite Terrane age, 3 Grenville age zircons, 1 Mid-Ordovician zircon, 1 Late Pennsylvanian, 1 Late Permian, and 3 Mid-Jurassic zircons. Despite the minimal number of zircons older than Upper Jurassic, these zircons are considered significant as they represent a spectrum of ages that would be predicted in the re

Lower Cretaceous Morita Equivalent Formations

Three volcanic tuff samples were collected that yielded Lower Cretaceous ages 2 of 124 Ma in the strongly folded belt north of Arizpe, Sonora and one age of 138 Ma 422 km to the south southeast of Arizpe at Zataque on the Sonora-Sinaloa border. All three tuffs crop out as part of a folded sequence consisting from bottom to top of black shale strata (host of the tuffs) beneath a limestone-marl-rudist limestone sequence and capped by marine reworked fluvial sandstone strata of the Cintura Formation. The outcrop at Zataque is considered to be thrust from the west side of the transpressional fault over a variety of rocks in the marginal basin ranging from Paleozoic crustal fragments to Upper Jurassic marine strata rich in volcanic debris. The Lower Cretaceous exposures from Zataque to Lluvia del Oro are strongly folded, but the underlying Upper Jurassic (e.g., north of Reforma, Chihuahua) through Lower Cretaceous (e.g., Gochico, Sonora) are much less deformed in this area of overthrusting.

At most localities the folded sequence is overlain by an angular unconformity capped by strata undeformed by shortening. These units are mostly clastic-rich units on the North American Craton such as the Cabullona Formation of northeast Sonora. Over the folded Bisbee Group or equivalents of the marginal rift basin variable thickness clastic units fill the paleo-valleys of the very irregular unconformity before being covered by Tarahumara age andesite (95-85Ma).

Upper Cretaceous Tarahumara Andesite

Dates are lacking on the Tarahumara Andesite in the areas mapped for this study, but its age is older than cross-cutting stocks and dikes making it older than the 88Ma stocks dated at Batopilas (see Appendix). This relationship indicate that these volcanic strata correlate with probable coeval Tarahumara volcanic rocks dated in central Sonora (McDowell and others, 2001) and associated stocks that cut the Tarahumara Andesite. Thus it can be inferred that the Tarahumara is 95 to 85 Ma. Numerous dates on stocks and dikes in the Batopilas district (Bagby, 1979, and this study) confirmed these dates. Wilkerson (1983) considered the unit he named the Tahonas the youngest unit but he was confusing much younger dikes with the stocks and dikes that dated as a part of this study (Appendix) throughout the district between 88 and 85Ma with U-Pb on zircons. Bagby (1979) obtained an 85Ma K-Ar date on a stock cutting the Tarahumara andesite on the northeast corner of the district.

The Tarahumara Andesites is considered to an entirely subaerial sequence of andesite flows and flow breccias with occasional dacite tuffs. The sequence shows no indication of being erupted into an aqueous environment. Minor reworking of tuffs and lapilli occurs between the many flows and flow breccias.

Eocene Rhyodacite

Rhyodacite flows and vents are found at the base of the Sierra Madre Occidental Volcanic Province (SMOVP) in many localities where the base of the SMOVP is exposed. Two localities were mapped as part of this study and the extensive flow found throughout the Batopilas region was dated as part of the mapping project. A sample of 30 zircons from the flow southwest of the silver district yielded an U-Pb age of 46.8 ±0.6Ma (Appendix). Wherever the age relationships these rhyodacite flows can be documented, they overlie Pre-Tertiary basement on a major angular unconformity and underlie the extensive Oligocene and Miocene rhyolitic welded tuffs of the SMOVP that cover most of the region.

Samples from the Central highlands of Mexico

Two samples from the central highlands of Mexico were collected to answer specific geologic questions.

Sierra Mojina and Sierra Santa Lucia, Chihuahua

Samples for detrital zircon dates were collected from an outcrop of the Las Vigas Formation at Sierra Mojina, Chihuahua and from an exploration drill core intercept from drill hole CM09-123 on the west flank of Sierra Santa Luciathe Las Vigas Formation in drill hole CM10-247at Sierra Santa Lucia. Sierra Santa Lucia, Chihuahua. One Archean zircon at 3.0Ga found itself here although possibly contamination along with the 85Ma zircon that based on stratigraphic position that is most certainly contamination.

Division del Norte, Chihuahua.

Division del Norte, Chihuahua is a small ejido 130 km east of Parral, Chihuahua and 60 km southeast of Jimenez, Chihuahua. Sample JL-DD-01 is a rhyolite flow located on the east side of vertical standing Aurora Limestone. The flow is flat lying where collected but its dip climbs to 45° along the east flank of the Aurora Limestone.

Sample Descriptions and Data

Samples dated are discussed here followed by a summary table. The first group of samples are from Batopilas, Chihuahua. These samples are mostly from igneous rocks of the district. The three exceptions are the molybdenite-quartz vein sample that was collected from the same locality as sample JL09-M1, 227,563.6E-2,993,519.9N UTM NAD 27 Mexico Zone 13.

Batopilas, Chihuahua.

The samples described below are on the listed in table A.1.

Table A.1 List of Batopilas Dating Samples, Descriptions, Locations, Age and Sample number. Table repeat of Table 3.1. Detailed data can be found in the supplemental files.

SAMPLE_NO	DESCRIPTION	EAST	NORTH	DATE	ERROR	N=	TECH	LAB_Analysist
JL-B9-M1	Qtz monz porphyry hosts JL-B9-M1A	227,563	2,993,520	88.1	±1.1	34	U-Pb	Boise State, V.Valencia
JL-B9-M1A	Qtz Mo vns cuttiing	227,609	2,993,493	84.4	±0.4	1	ReOs	U of Arizona, Barra
JL-B9_M2	Injected Qtz Monz Por in bx dike	227,535	2,993,577	54.9	±0.8	34	U-Pb	Boise State, V.Valencia
JL-B9-M3	Qtz monz porph cutting Dolores diorite	226,692	2,992,564	55.2	±0.8	29	U-Pb	Boise State, V.Valencia
JL-B9-L1	Qtz latite porph cutting qtz monz porph	227,209	2,991,784	28.9	±0.5	33	U-Pb	Boise State, V.Valencia
JL-B9-M4	Qtz monz porph + qtz stockwork flooded	226,658	2,991,258	88.1	±1.3	32	U-Pb	Boise State, V.Valencia
JL-B9-M5	Qtz-monz-porph Kspar-epidote Alt	226,711	2,991,401	88.7	±1.8	32	U-Pb	Boise State, V.Valencia
JL-B9-L3	Latite-porph dike	226,828	2,991,436	72.7	±0.9	30	U-Pb	Boise State, V.Valencia
JL-B9-M6	Quartz-monzonite-porphyry at Batopilas	228,182	2,992,005	86.8	±1.1	30	U-Pb	Boise State, V.Valencia
JL-B9-M7	Qtz-monzonite-porphyry on Animas road	228,710	2,995,660	87.8	±1.0	30	U-Pb	Boise State, V.Valencia
JL-B9-M8	Qtz monz-porph Core BA08-24; 556m	227,657	2,994,649	88.2	±1.2	32	U-Pb	Boise State, V.Valencia
JLB-V-1	Satevo Rhyodacite	223,651	2,989,721	46.8	±0.6	30	U-Pb	U of Arizona, V. Valencia
JLB-L-1	Qtz-latite-porph cutting Minas Member	228,648	2,993,194	85.7	±1.1	30	U-Pb	U of Arizona, V. Valencia
JLB02	Roncesvalles sandy strata, detrital	228,549	2,994,123	149		100	U-Pb	U of Arizona, V. Valencia
JLB01	sandstone at base of KVAC, detrital	229,222	2,992,035	85		10	U-Pb	U of Arizona, V. Valencia
JL-B9-D1	Dolores Diorite	226,389	2,992,852	54.6	±1.2	11	U-Pb	Boise State, V.Valencia

Sample JLB-V1 is a sample of a rhyodacite flow, the Satevo Rhyodacite, found at the base of the Yerbanis Oligocene Rhyolite tuffs. It is located at 223,651E 2,989,721N NAD27 Zone 13. The age is based on analysis of 30 zircons is 46.8 ±0.6 Ma (see Supplemental Data).

Jl-B9-D1 is a sample of Dolores Diorite sampled for comparison purposes with the Rb/Sr date acquired by Bagby (1979) and the K/Ar date from Wilkerson and others (1988). The sample location is 226,389E-2,992,852N UTM NAD 27 Mexico Zone 13 along the creek to the Caballo Mine area. The diorite is cut by a 1 to 2 cm calcite galena vein azimuth 180° dipping 70°W. A U-Pb date was obtained from 11 zircons of 54.6 ±1.2 Ma. The Rb-Sr date obtained by Bagby (1979) was 50 Ma and the K-Ar biotite date reported by Wilkerson and others (1988) was 51.6±1.1 Ma.

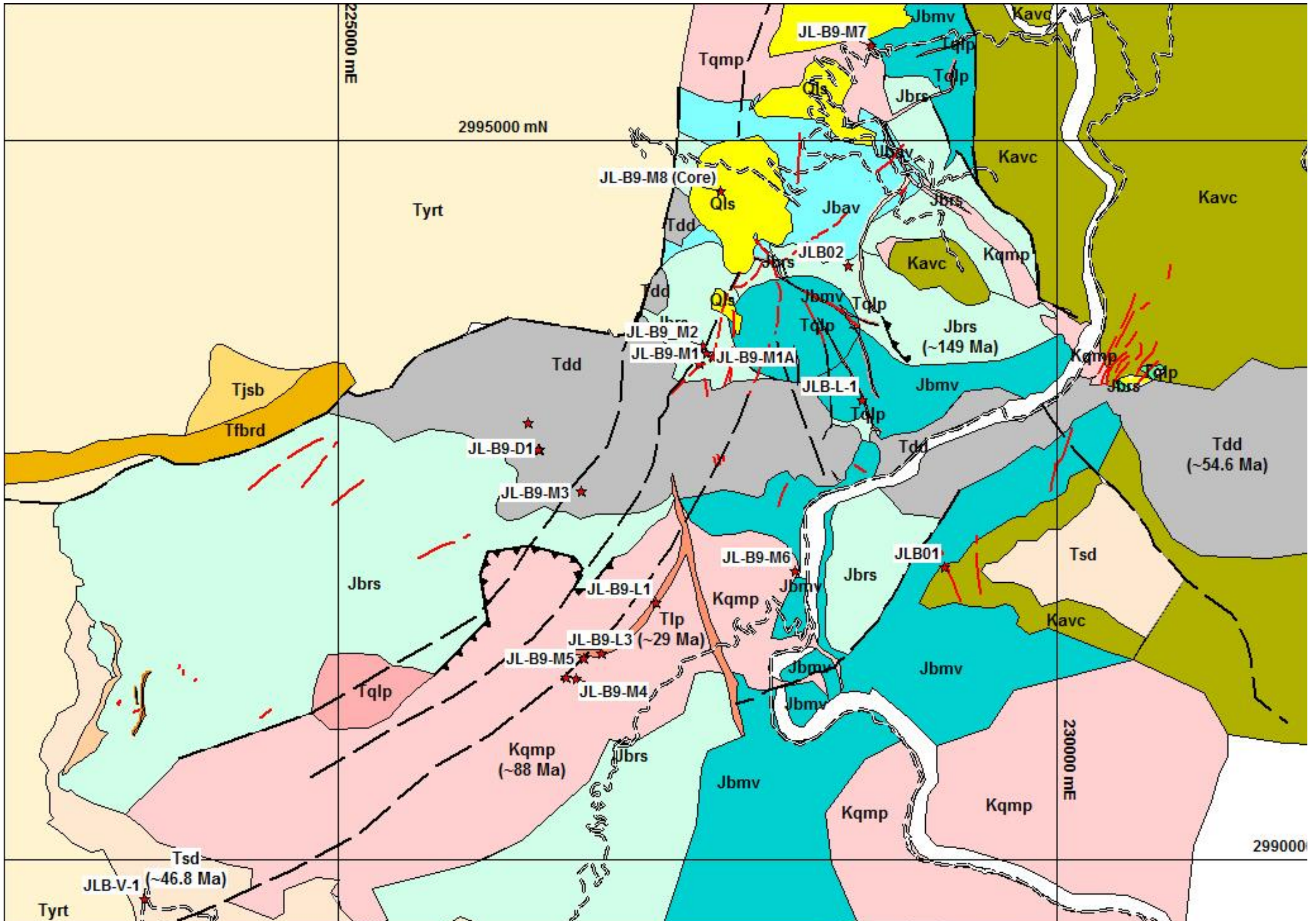

Figure A.1 Map of the Batopilas, Chihuahua District with dated samples labeled.

Jl-B9-L1 is a sample from a 7.0 m wide dike that cuts both the Dolores Diorite and the Tahones Quartz Monzonite. The sample is located 227,209E-2,991,784N UTM NAD 27 Mexico Zone 13 just east of the major junction in the major east draining creek that joins the Batopilas River at the south end of town. The dike consists of Kspar phenocrysts in an aphanitic groundmass. The dike was dated at 28.9±0.5 Ma from 33 zircons. This is the youngest igneous rock dated in the district and appears to be a feeder to part of the Oligocene Yerbanis tuffs and flows.

JL-B9-L3 is a sample of a latite porphyry dike from the Corralitos area. The sample was located at 226,828E-2,991,436N UTM NAD 27 Mexico Zone 13 just east of the previous samples. It is a vertical dike with an azimuth of 100°. The dike is mostly aphanitic with sparse plagioclase. Sample JL09-L3 was dated at 72.7±0.9 Ma from 30 zircons. This date suggest the Early Laramide episode of magmatism and is the only date representing this period collected in the Batopilas area.

Sample JL-B9-M1 is of a quartz monzonite porphyry dike that hosts the molybdenite bearing quartz vein sampled for a Re-Os date on the molybdenite. The sample was located on the Porfirio Diaz Tunnel level in the hanging wall of the Todos Santos Vein between it and the Roncesvalles Vein at 227,563.6E-2,993,519.9N UTM NAD 27 Mexico Zone 13. The sample JL09-M1 yielded an U-Pb age of 88.1±1.1 Ma from 34 zircons.

At the same locality as sample JL-B9-M1 a sample of the molybdenite rich quartz vein was sampled for a Re-Os date on the molybdenite. This analysis yielded an age of 84.4±0.4 Ma, slightly younger than the Tahonas stocks

JL-B9-M2 samples an unusual diorite porphyry breccia found on the Porfirio Diaz Tunnel level back along the Roncesvalles Vein on the level of the vein. The sample is located at 227,535.2E-2,993,576.5N UTM NAD 27 Mexico Zone 13. The sample is of one plastically deformed fragment of many in the breccia ore shoot noted on the 1910 era maps of the mine (Wilkerson,.1983). The ore shoot was mined because of the abundant banded silver-calcite vein fragments mixed with the irregular igneous masses dated, in a rock flour matrix. Sample JL09-M2 yielded an U-Pb date of 54.9±0.8 Ma from 34 zircons. The apparent plastic behavior of the diorite fragments mixed with ore fragments suggests they were still molten during emplacement but that the ore fragments were pre-intrusion. The mixing of banded ore fragments with apparently molten igneous fragments of the same age as the Dolores Diorite suggests that the banded silver-calcite veins are pre-Dolores.

JL-B9-M3 is a sample of a 0.5 m wide quartz monzonite porphyry dike that cuts the diorite porphyry and was sampled to investigate the age of a post diorite dike. The sample location is 226,692E-2,991,784N UTM NAD 27 Mexico Zone 13 along the same creek as the previous sample, to the Caballo Mine area. The quartz monzonite porphyry contained quartz dipyramids and K-spar crystals to 1 cm in size. The U-Pb date obtained from 29 zircons was 55.2±0.8 Ma slightly older but within the range of error indicating that it may be a late phase dike of the Dolores Diorite.

JL-B9-M4 is a sample of the Corralitos quartz monzonite porphyry. The sample is located at 226,658E-2,991,258N UTM NAD 27 Mexico Zone 13 in the area of the Corralitos exploration project of Peñoles. The outcrop area was cut by an intense quartz vein stockwork with a strong east dominate orientation. Sample JL-09-M4 was dated at 88.1±1.3 Ma from 32 zircons.

Sample JL-B9-M5 also comes from the Corralitos quartz monzonite porphyry. The sample is located at 226,711E -2,991,401N UTM NAD 27 Mexico Zone 13 on the other side of the creek from JL-B9-M4. It was selected because of the much more intense alteration at JL-B9-M4 than the Kspar-epidote alteration in this sample. Sample JL09-M5 was dated at 88.7±1.8 Ma from 32 zircons.

Sample JL-B9-M6 sampled the Tahones quartz monzonite porphyry. The sample location is 228,182E-2,992,005N UTM NAD 27 Mexico Zone 13. The outcrop is cut by a weak low angle quartz vein 1cm wide. Sample JL09-M6 was dated by U-Pb at 86.8±1.1 Ma from 30 zircons.

JL-B9-M7 is a sample of a quartz monzonite porphyry from north of Animas ridge along the road climbing to the top of Animas ridge. The sample was collected to determine whether this stock is of the same suite of rocks as Tahones and Corralitos. The location is 228,710E-2,995,660N UTM NAD 27 Mexico Zone 13 on the north side of the road in the switchback at that location. The quartz monzonite porphyry is altered with crosscutting K-feldspar veins Sample JL09-M7 yielded an U-Pb age of 87.8±1 Ma from 34 zircons.

Sample JL-B9-M8 is a quartz monzonite porphyry collected from the bottom of drill hole BA08-24 at 556.0m depth. The collar location of BA08-24 is 227,657E 2,994,649N UTM NAD 27 Mexico Zone 13. Sample JL09-M8 yeilded 88.2 ±1.2 Ma from 32 zircons.

Sample JLB-V-1 was collected from the Satevo Rhyodacite Flow (224,139E 2,989,641N UTM NAD 27 Mexico Zone 12R) that crops out extensively in the southwestern part of the map area. It consists of a quartz porphyry rhyodacite flow situated between the overlying Oligocene-Miocene Yerbanis tuffs and flows and the underlying Jurassic and Cretaceous strata. Sample JLB-V-1 yielded a U-Pb date of 46.8 Ma ±0.6 from 30 zircons. This Middle Eocene flow is the only Eocene unit known in the immediate area. It correlates with many Eocene flows and flow domes found at the base of the Oligocene SMOVP.

Sample JLB-L-1 is a latite porphyry dike located at 228,648E 2,993,194N UTM NAD 27 Mexico Zone 12R in the arroyo Minas. This latite porphyry dike yielded an U-Pb age of 85.7 Ma ±1.0 from 30 zircons.

Sample JLB01 was collected from the unconformity located at 229,222E 2,992,035N UTM NAD 27 Mexico Zone 12R. If the mapping is correct the 73 Ma zircon is contamination. As indicated in Fig. A.2, only 10 zircons were separated from the sandstone dominated by Tarahumara 83 to 88 Ma zircons.

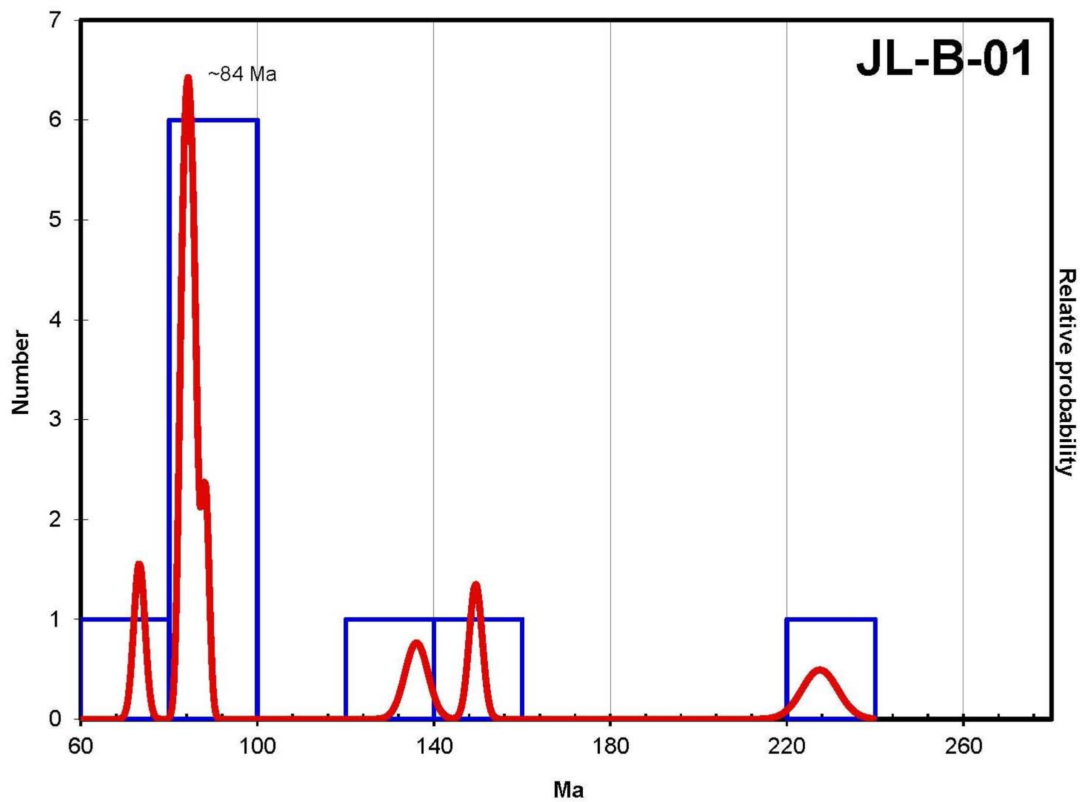

Figure A.2 Sandstone sample JL-B-01 from the unconformity at the base of the Tarahumara.

Sample JLB02 was collected from the Roncesvalles Member of the Batopilas Formation. Shale with volcanic debris & Belemnite frags. Sample location is NAD 27 Zone13 Mexico 228,549E, 2,994,123N. A U-Pb age of 149 Ma is indicated by 80 zircons from the Upper Jurassic with a very dominant peak at 149 Ma.

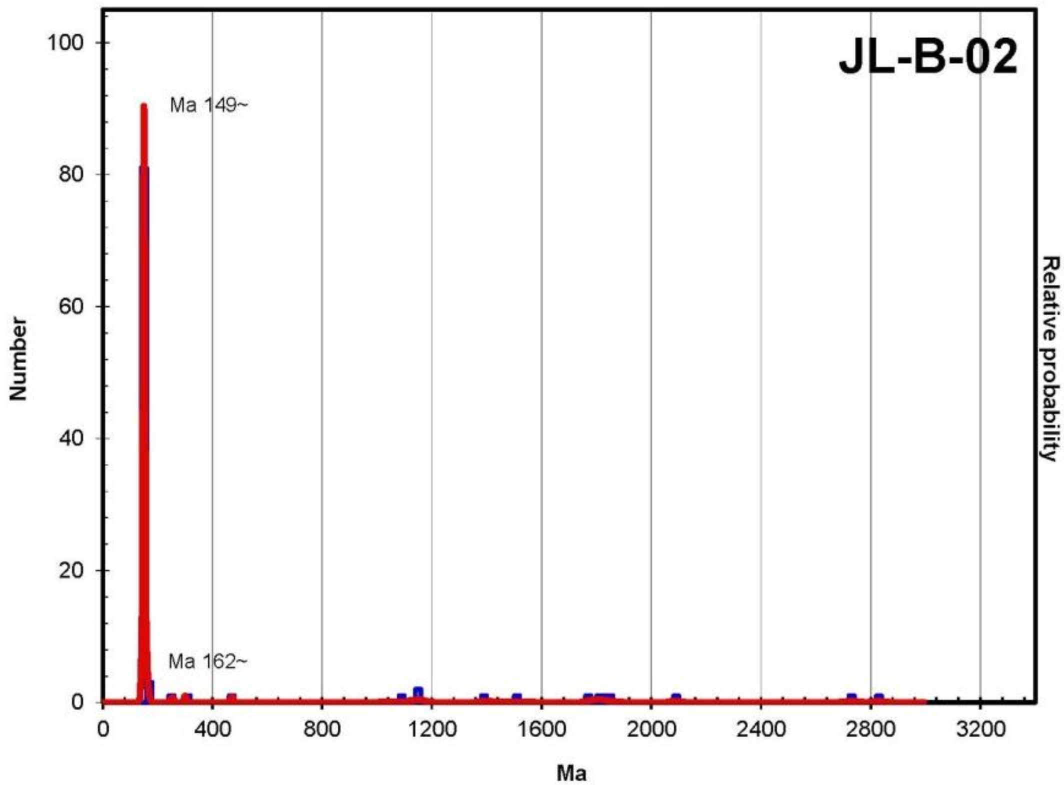

Figure A.3 The relative probability plot of sample JL-B-02 from the Roncesvalles Member of the Batopilas Formation between the two dacite flow domes at Batopilas.

Moris, Chihuahua samples

The Moris, Chihuahua area is located in JLM1 is a sample of a pink granite porphyry that cuts the gneiss at the north end of the basement exposure at Moris, Chihuahua. Granite sample JLM1 has a U-Pb date of 1442.6±17.6 Ma (N= 30).

Samples JL-MS-1 and JL-MS-2 were collected from 744,539E 3,123,122N and 744,206E 3,123,074N respectively UTM NAD 27 Zone12R. Both sandstones yielded only Precambrian zircons (Figs. A.4 and A.5) believed to be derived from the upslope Paleozoic quartzite. The paleontologically determined Tithonian marine strata appear to lap on to the quartzite and is thus interpreted that the quartzite is the source of the analyzed zircons..

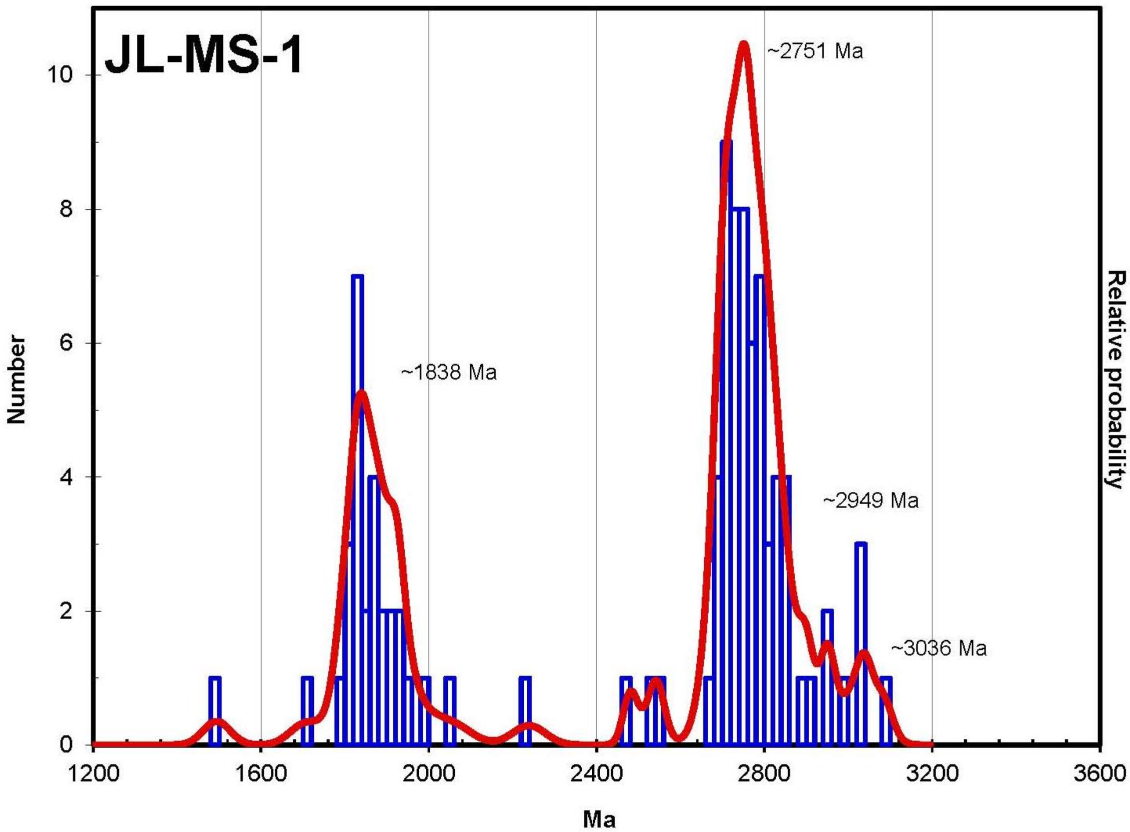

Figure A.4 The relative probability plot for zircons extracted from sample JL-MS-1 from Moris, Chihuahua. Major Yavapai and Archean peaks dominate the plot.

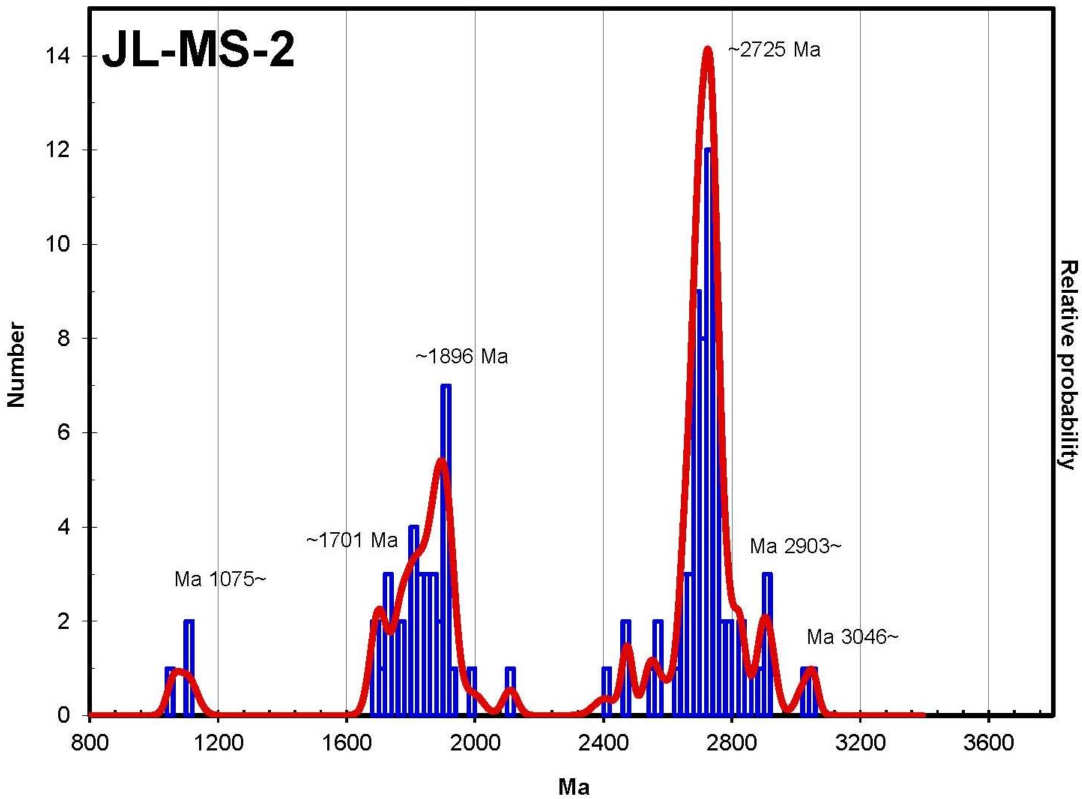

Figure A.5 The relative probability plot for sample JL-MS-2 from Moris, Chihuahua displaying Grenville, Yavapai and Archean zircons.

Zataque, Sonora-Sinaloa Samples

Sample JL-MO-01 was collected at 749,697E, 2,975,566N (NAD 27 Zone12) from the major arroyo trending east-northeast from the village of Zataque, Sinaloa. The sample is located in a tuff bed within steeply dipping strata correlated with the Morita Formation of the Bisbee Group. Figure A.6 shows that the 135 to 138 Ma age of the majority of zircons indicates that JLMO-01 is essentially an igneous age on the source of the tuff.

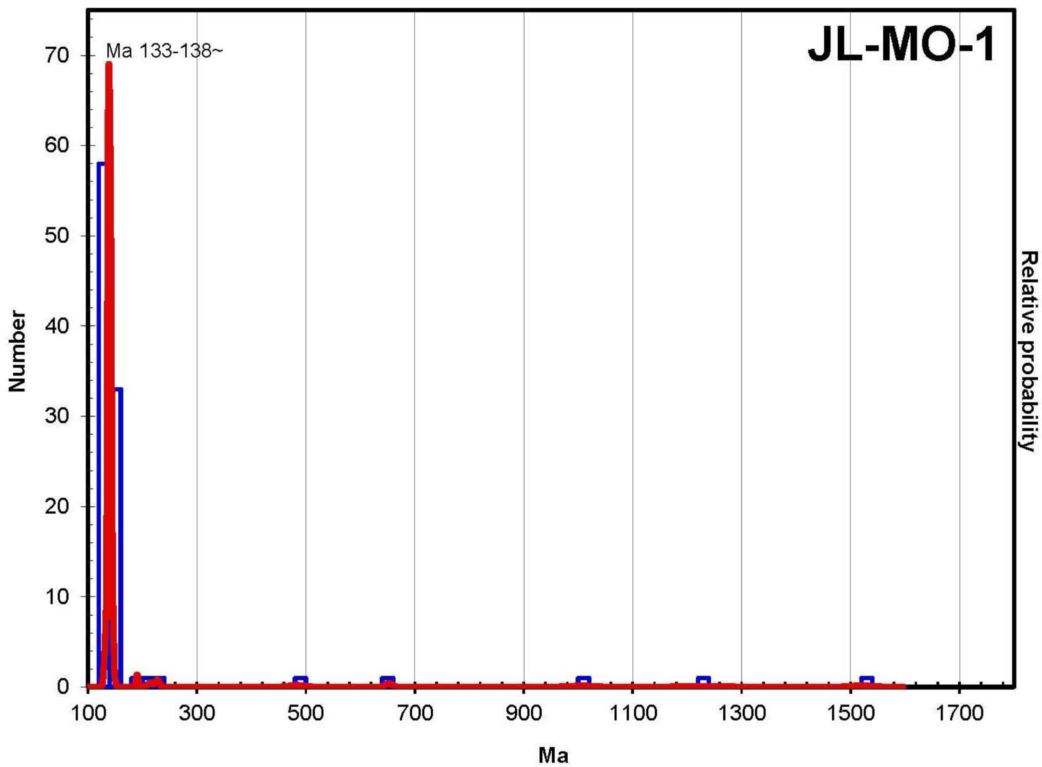

Figure A.6 The relative probability plot for sample JL-MO-1 from Zataque, Sinaloa.

Sample JL-MO-02 was collected from 743,152E, 2,981,953N (NAD 27 Zone12) from the major arroyo cutting the northwest quadrant of the Zataque map. The rock sampled consisted of conglomeritic sandstone from the clastic sequence located on the major angular unconformity between the folded Bisbee Group equivalent strata and the northwest dipping andesite regionally correlated with the Upper Cretaceous Tarahumara Formation. It includes zircons from the Tarahumara volcanism as well as Late Jurassic and Early Triassic magmatic events.

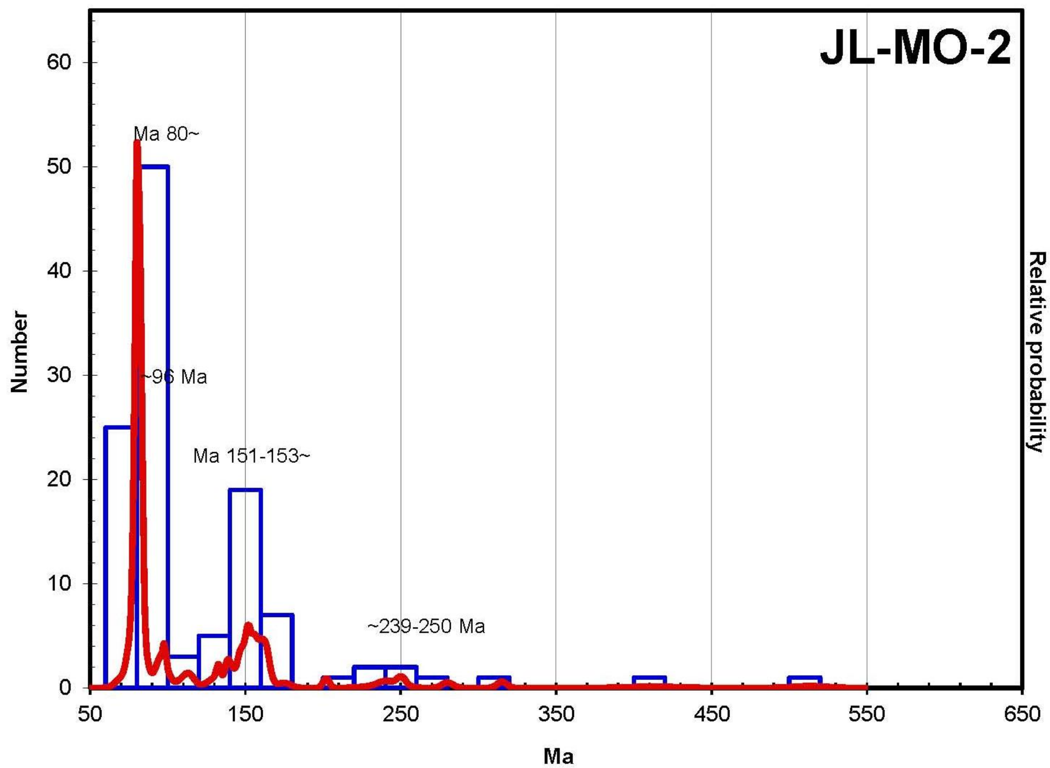

Figure A.7 The relative probability plot for sample JL-MO-2 from Zataque, Sinaloa.

Division del Norte

Sample JLDDN-1 was collected from a rhyolite flow on the northeast side of the range at east of Division del Norte, Chihuahua at 562,948E, 2,979,451N UTM NAD 27 Zone 13. It was noted in the field that the relatively flat-lying flow appears to be folded up to approximately 40° on the northeast flank of the near vertical beds of the Aurora Limestone that make up the range at Division del Norte. The age as indicated in Fig. A.8 is 43.7 Ma

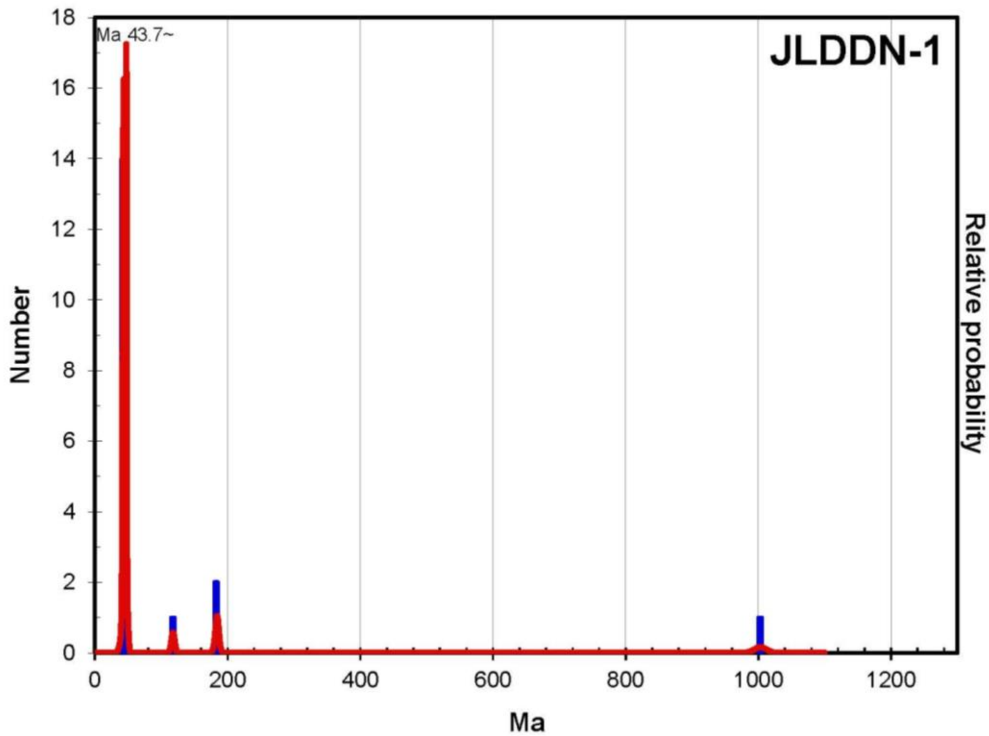

Figure A.8 The relative probability plot for sample JLDDN-1 from Division del Norte, Chihuahua indicates an igneous age of ~43.7.

Analysis of 31 zircons from JLDDN-1 (Fig. A.9) yielded a TuffZirc age of 43.7 +1.5 -0.8 Ma.

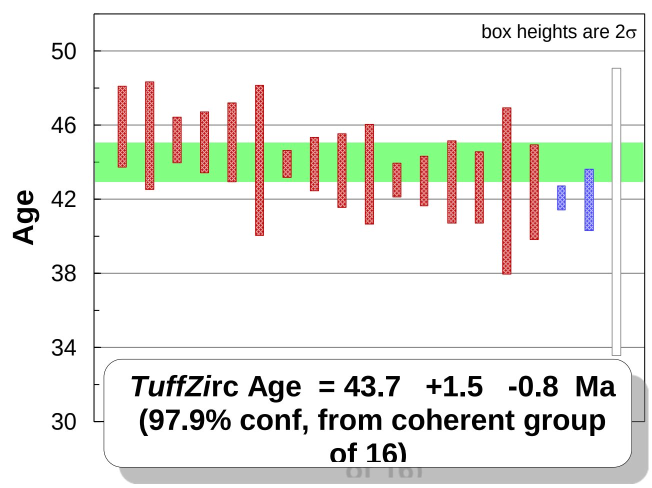

Figure A.9 A TuffZirc age of JLDDN-1.

Sierra Ramirez, Durango

Sierra Ramirez is located in eastern-most Durango. It crops out as a west-northwest trending range consisting of south-southwest directed out of the basin thrusting along the south margin of the Mexican Basin. The thrust sheets consists mostly of Upper Jurassic and Lower Cretaceous carbonate strata with some windows into dacitic welded tuffs and sandstone strata. Sample JL-SR-1 was collected from one window to verify that the volcanic strata was indeed Nazas strata as mapped or possibly Oligocene volcanic strata that was overthrust by the Jurassic and Cretaceous strata. It was found located along an old mine road at 732,969E, 2,753,877N UTM NAD 27 Zone 13. The dating of 50 zircons from the sample confirmed a Middle Jurassic age for the tuff.

Sample JL-SR-01 produced a broad spectrum of ages (Fig. A.10) with the majority falling in a 15 Ma year period from 170 to 185 Ma. A TuffZirc calculation (Fig. A.11) yielded 171.5 Ma from a coherent group of 13zircons. This spread of ages is interpreted to reflect the 171.5 Ma caldera eruption cutting through a volcanic pile that initiated at approximately 185 ma.

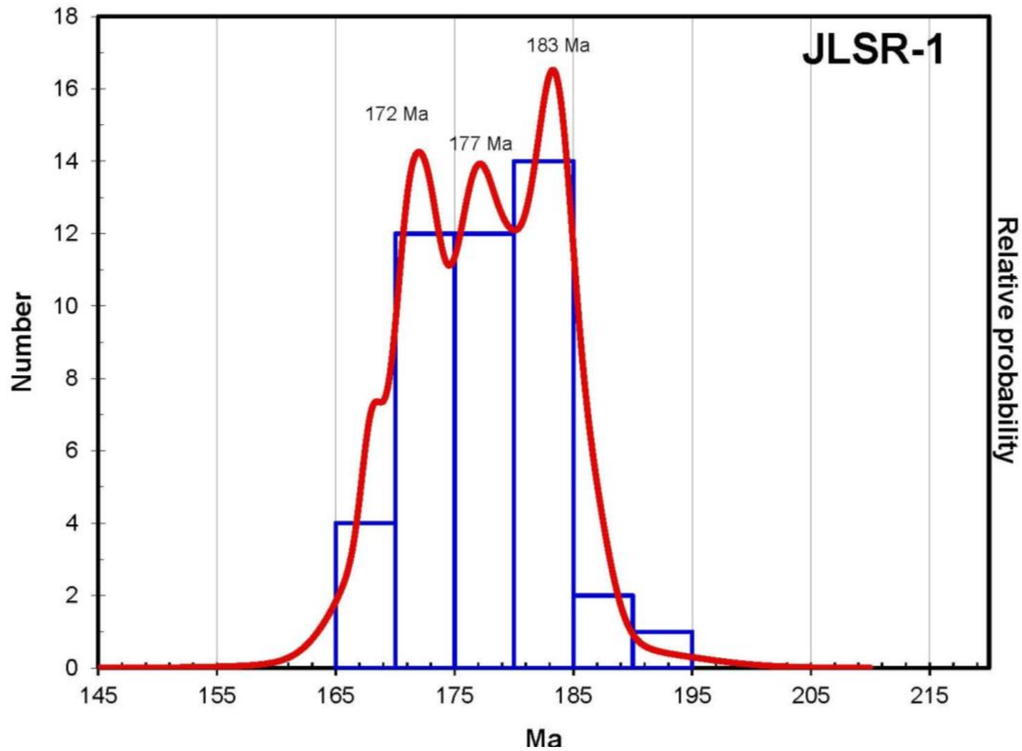

Figure A.10 Relative probability plot for sample JLSR-1 illustrating the broad peak of 15 Ma.

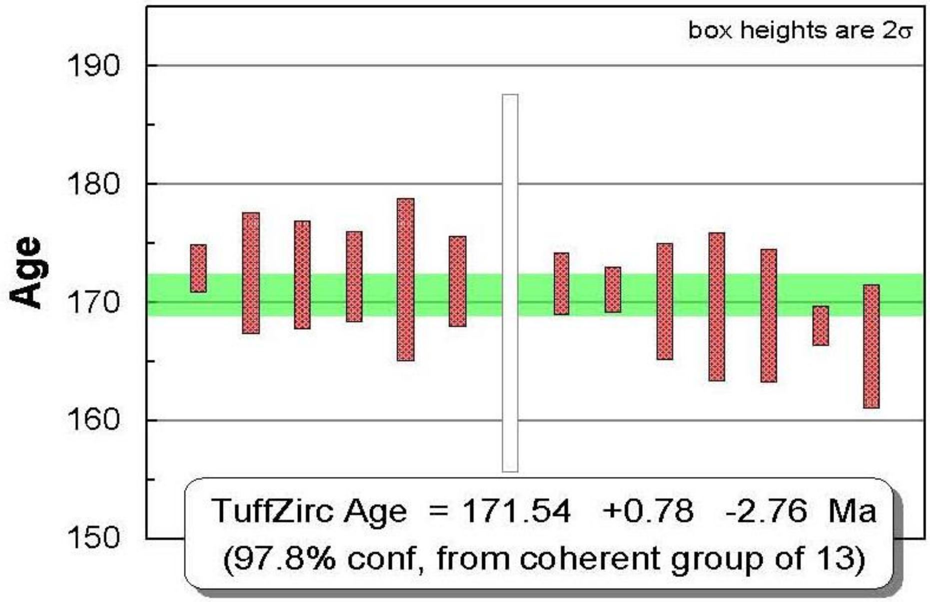

Figure A.11 TuffZirc age for the rhyodacitic eruption at Sierra Ramirez, Durango.

Sierra Santa Lucia, Chihuahua

Sierra Santa Lucia is located 200 km north-northwest of Chihuahua City on the west side of the Ejido Benito Juarez. The Lower Cretaceous Las Vigas Formation does not crop out in the range but was intersected in a number of exploration drill holes on the west side of the range. Sample JLCM-1 was collected MAG Silver's core drill hole CM10-247 (303,158E, 3,339,942N UTM NAD 27 Zone 13R) at 861 m depth. The sample consisted of about 1m of clean conglomeritic quartz sandstone resting directly on propylitically altered arkosic mudstone.

The thin quartz rich nature of the unit suggest that it may contain a significant reworked zircon content derived from the underlying Permian Scherrer Formation. Further support comes from the distinct zircon populations at Santa Lucia and Sierra

Mojina with the Sierra Mojina sample appearing to come from a source other than the Scherrer.

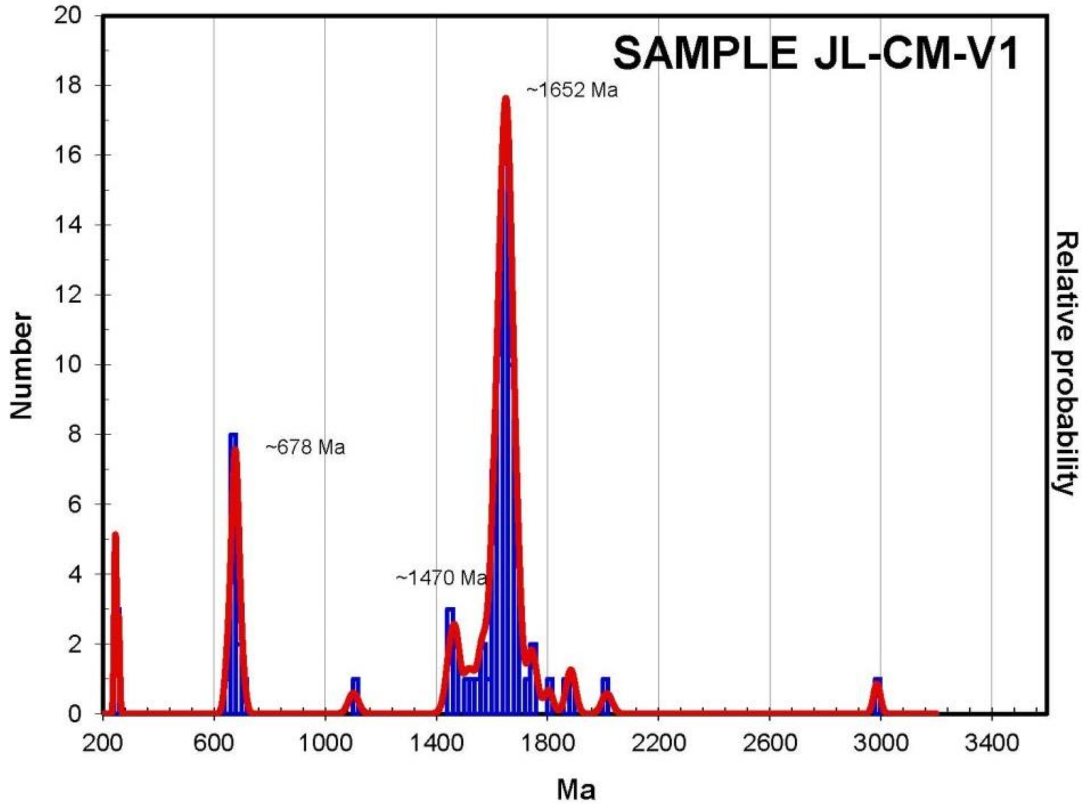

Figure A.12 Relative probability plot of the data for sample JL-CM-V1.

Sample JLMJ-01; Sierra Mojina, Chihuahua

A sample of the Lower Cretaceous Las Vigas Formation JLMJ-01 was collected for detrital zircon analysis from the east flank of Sierra Mojina 160 km north northwest of Chihuahua City at 323,365E, 3,305,376N UTM NAD 27 Mexico Zone 13. The conglomeritic strata was overlain by the calcareous shale of the Lower Cuchillo Formation and underlain by propylitically altered (piedmontite, epidote and minor wollastonite) arkosic mudstone with caliche nodules. The sample consisted of a conglomerate of clast of redish gray micaceous schist and white quartz vein material in a red sandy matrix (Figs. 4. Isolated clast of red rhyolite and a light colored granitiod were observed in outcrop but not in the collected sample.

The near monolithic nature of the schist clast in the Las Vigas suggests that a major component of zircons should come from the dominant clast source unit with an unknown amount of mixing from syndepositional drainage transport and the underlying Scherrer arkosic sandy mudstone.

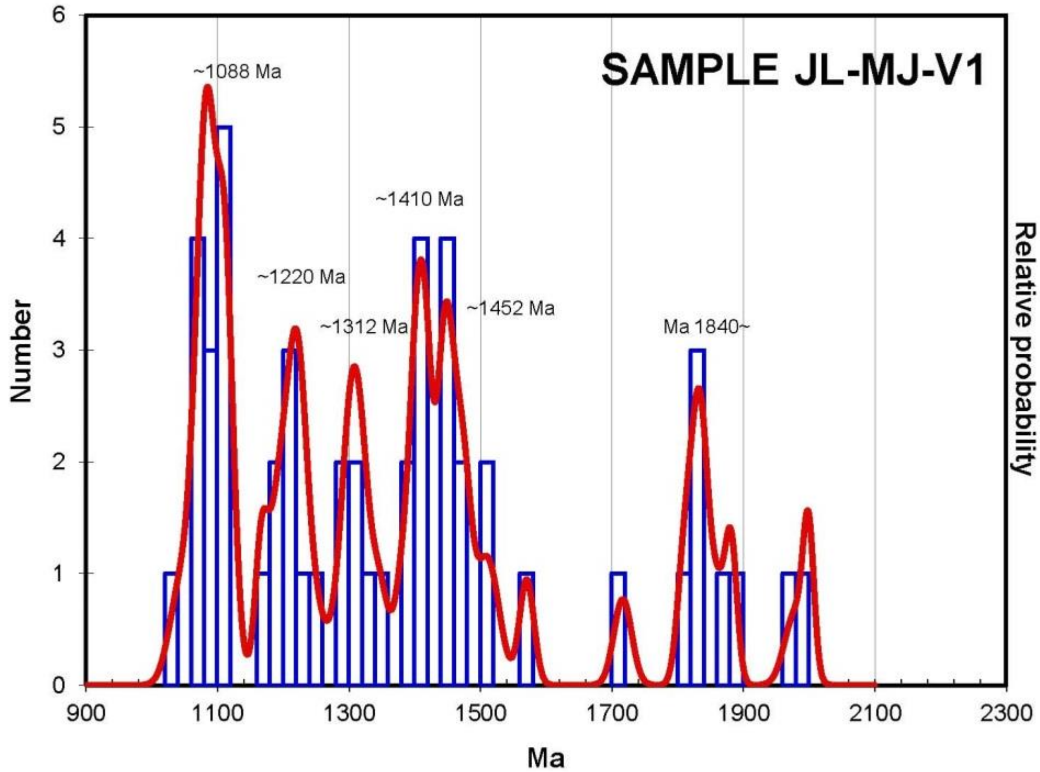

Figure A.13 Relative probability plot for sample JL-MJ-V1.

Appendix B. Geological and Geochemical evidence for a Mesozoic marginal basin in western Mexico- The Mezcalera Marginal Basin: Implications for regional ore genesis in Northwest Mexico,

A revised version of the published paper:

Lyons, J. I., 2008, Geological and Geochemical evidence for a Mesozoic marginal basin in western Mexico: Implications for regional ore genesis in the Guerrero province, *in* Spencer J.E., and Titley, S.R., eds., Ores and Orogenesis: Circum-Pacific tectonics geologic evolution and ore deposits: Arizona Geological Society Digest 22, P357-368.

Geological and Geochemical evidence for a Mesozoic marginal basin in Western Mexico- the Mezcalera Marginal Basin: Implications for regional ore genesis in northwest Mexico

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ABSTRACT

Field mapping of widely distributed Jurassic marine sediments and submarine volcanic rocks in western Mexico support reinterpretation of the Guerrero as a continental marginal basin (here renamed the Mezcalera) initiated by extension possibly starting in the Triassic rather than an accreted arc terrane. Regional mapping indicates that the Cananea Trend, a well-known alignment of porphyry copper districts in northern Mexico, reflects a major fault separating the North American Craton from the extended cratonic crust floor of this marginal rift basin. Early to Middle Jurassic silicic volcanic rocks and clastic sediments fill the northern portion of the marginal basin and transition to dominantly marine shale, mudstone, turbidites and submarine volcanic rocks (Late Jurassic where dated). These sediments extend from central Sonora at least as far south as southwestern Durango State. Multi-kilometer scale blocks of Proterozoic and Paleozoic, sometimes found surrounded and partially covered by the Jurassic sediments, appear consistent with extended crust.

Tourmaline occurrences and Mo systems crop out principally in Laramide stocks, batholiths and coeval volcanic phases in a belt from Southwestern Arizona to at least as far south as Mazatlan, Sinaloa. Both the tourmaline and Mo principally occur where the

Laramide batholiths cut the proposed continental margin basin. The abundance of tourmaline in these systems suggests assimilation or hydrothermal extraction by the magmas of boron from boron enriched shale from the basin and by inference the Mo as well. Porphyry copper deposits along the Cananea Rift Margin contain more tourmaline and Mo (greater than 0.015 % Mo) than is typically found elsewhere in the southwestern North America porphyry province to the east. Porphyry mineral systems within the proposed marginal basin shale-turbidite-volcanic province are more typically Mo deposits rather than Cu deposits. The typically younger Au deposits within the proposed basin limits represent a major part of Mexico's total Au resource. The coincidence of tourmaline and many of the Mo and Au systems in the region with the Jurassic marine sediment belt suggests a genetic tie. While the correlation is not near as strong for gold, it may also be reflecting a genetic tie.

INTRODUCTION

The principal proposed model for the distribution of metals in Mexico by Clark and others (1982) ties metal distribution to the inward and return sweep of continental magmatism resulting from the varying dip of the subducting Pacific oceanic plate under Mexico since the Jurassic. They proposed that the distribution of the various mineral belts, parallel to the subducting margin, clearly ties the mineral belts to the evolution of the subducting plate rather than crustal variation. Valencia and others (2006) proposed, that general patterns of basement distribution along Mexico's west coast was reflected in variations of porphyry copper style mineralization in the region.

Campa and Coney (1983) first introduced the Guerrero as a suspect accreted terrane in their tectonic model of Mexico. This model has acquired general acceptance with a variety of modifications by subsequent authors. Sedlock and others (1993) divided and renamed Guerrero with a complex accretionary and translational construction of most of the Mexican Craton. Dickenson and Lawton (2001) proposed recombining the Guerrero and added Baja California as part of an accreted oceanic arc of their Guerrero superterrane. Centeno (2005) preferred keeping the Guerrero as a composite terrane because of evidence of continuity within the terrane during the Cretaceous.

As the Guerrero accretion model has evolved, other authors have been accumulating evidence which appears inconsistent with an accretionary arc model. Malpica (1972) recognized Carboniferous fossils in the San Jose de Gracia area on the Sinaloa-Chihuahua border. This Paleozoic zone extends to the west into the El Fuerte region (Mullen, 1978) east of the Triassic Francisco Gneiss. This block of Paleozoic forms the Rusias Terrane of Campa and Coney (1983). Henry and Fredericson (1987) recognized Paleozoic sediments near Mazatlan. Gastil and others (1991) confirmed Malpica's observations of Paleozoic sediments. Centeno and others (1993) determined that the provenance of the Arteaga Triassic gneiss of western Michoacan included Paleozoic and Precambrian zircons. Lang and others (1996) found no stratigraphic or structural discontinuities which required accreted terrane boundaries in southern Mexico. Lyons (2002) proposed the Cananea-Inde fault as a Triassic rift margin of west Mexico separating Late Paleozoic North America from a Jurassic marginal rift basin. Lawton and others (2003) have been mapping outcrops of Jurassic basin sediments in the Cucurpe area of central Sonora. Because of the lack of a comprehensive study of the Jurassic in western Mexico, Lawton and others (2003), Anderson and Nourse (2005) and Haenggi and Muehlberger (2005) proposed the Cucurpe Basin as one of a system of pull apart basins in which the Jurassic marine sediments accumulated. Keppie and others (2006) interpreted the Francisco Gneiss on the Sonora-Sinaloa border as having formed in a Triassic rift environment.

The purpose of this paper is to present evidence for the development of a Jurassic marginal rift basin in western Mexico, document the distribution of certain types of metal enrichments in this region, and to suggest a model that relates the origin of the mineralization with the proposed marginal basin. This study has been part of a career long study of Mexican geology including its ore deposits, volcanic rocks, and regional basement and tectonic history. It is one of a planned series of articles documenting these observations and the resulting interpretations.

JURASSIC MARINE OUTCROPS OF WESTERN MEXICO

The intention of this discussion is to define the Mezcalera Rift Basin spatially, reserving the detailed observations, which define the basin as a marginal rift basin, for other venues. The dominant assemblage of these proposed Jurassic rocks are black, carbon-rich, deep water marine shale typically with thin distal sandy turbidite flows. Outcrops of this lithology extend from north central Sonora to southwest Chihuahua. Studies in progress by Lawton and others (2003) and Peryman and others (2005) have advanced current knowledge of Late Jurassic sediments in the Cucurpe area of north central Sonora with mapping and U-Pb provenance studies. Villasenor and others (2005) interpret ammonite and belemnite fossils found at Cucurpe as Late Jurassic in age. This study is expanding the provenance studies to Batopilas and Moris, Chihuahua and Arizpe, Sonora and fossil studies to Batopilas.

A plot of the distribution of known marine Jurassic and Cretaceous deep water sediments in western Mexico (Figure B.1) illustrates the basis for the proposed Jurassic marginal rift basin. Most structural boundaries to the basin result from the projection of many isolated mapped segments which reveal the major stratigraphic changes across them. The most important of these is the Cananea rift margin fault (Figure B.1) that separates the basin from the North American Craton.

The principal lithologic variation, from the deep marine shale, observed in this study consists of thin bedded mudstone, shale and sandstones believed to be more representative of the slope environment. This lithology crops out at Parral, Chihuahua; Chirimoyo, Durango; and Sara Alicia, Sonora. The only known age determination on this group of sediments is Late Jurassic and Early Cretaceous at Parral carried out by PEMEX (L. Garza, personal communication).

In north central Sonora, Early to Middle Jurassic volcanic rocks with some interbedded arenite units dominate the Jurassic section. Limited localities of Late Jurassic marine shale occur southwest of Nogales, Sonora. To the south the Late Jurassic sediments begin to dominate the exposed Jurassic section. Moris and Batopilas, Chihuahua, contain similarly altered andesitic rocks emplaced in the dominant marine sedimentary section.

Newly mapped or reinterpreted outcrops, which reveal geologic relationships important to understanding the Jurassic history of the region, include Batopilas, Chihuahua; Moris, Chihuahua; and Arizpe, Sonora. Additional outcrops such as Arivechi, Chirimoyo, Rio Mulatos, Sara Alicia and others still need more study.

Batopilas, Chihuahua.

The Batopilas quadrangle (INEGI geologic quadrangle G13A41) does not indicate any Jurassic sedimentary or volcanic rocks in the Batopilas Silver District (Fig. B.1) nor does the district study of Wilkerson and others (1988). New mapping by the author confirms unpublished company reports of sediments and expands their extent to make these sediments and associated volcanic rocks the major host rock to the silver veins in the district. The sediments consist of deep marine sediments, turbiditic sandstones and interfingering andesitic volcanic rocks. Preliminary fossil identification (T. Lawton, personal communication) suggests that the ammonites, belemnites, gastropods and pelecypods encountered correlate with those identified in the Jurassic Cucurpe Formation (Villasenor and others, 2005) 500 km to the northwest of Batopilas. The marine sediments interfinger with the highly altered andesite flows and flow breccias of two stacked submarine volcanic sequences. Wilkerson and others (1988) referred to these igneous rocks as the Pastrana Dacite but lumped all of the sediments with the igneous rocks. Strong albitization (Na) of the plagioclase in the submarine environment appears to have confused the rock type definition, but Wilkerson's own chemical data (1983) plots as andesitic in composition. A provenance study of turbiditic sandstones from the marine shale is currently in progress to aid in understanding the origin and age of the turbidites and marine shales.

Moris, Chihuahua.

Jurassic shale is located southeast of Arivechi, east of Pilar de Moris and north of the village of Moris (Fig. B.1) on the INEGI H12-12 Tecoripa geologic quadrangle map. Proterozoic gneiss is also indicated to the north of Moris and possible Proterozoic limestone and sandstone are plotted to the east of Moris. Remapping in this study indicates a very different distribution of rocks with two blocks of Proterozoic gneiss capped with a basal Paleozoic quartzite and overlying Paleozoic limestone. These two basement blocks protrude up to 500 meters into the black shale interbedded with distal turbidite sandstones, exhibit differing structural orientations and are separated from each other by these sediments at the base of the 500 meters of exposed relief. The shale also contains andesite dikes, sills and igneous breccia pipes with very similar lithologies to those found at Batopilas. A clear syndepositional relationship occurs at Batopilas but has not been proven at Moris. The gold mine 5 km north of Moris, Chihuahua (H12D87 50k topographic quadrangle) occurs in mineralized Jurassic and Paleozoic sediments where an altered felsic porphyry dike cuts them.

Arizpe, Sonora.

Nine kilometers north of Arispe, Sonora (Fig.B.1), mapping by Gonzales-Leon and others (2000) indicates a sequence (from bottom to top, east to west): the Bisbee Group, a thrust fault, a new unit, the Picacho Conglomerate followed by a second thrust slice of Bisbee group where the highway cuts Cerro El Puerto. This study suggest that Morita, Mural and Cintura crop out on the northeast side of Cerro El Puerto and does not correlate with the shale turbidite sequence that crops out on the southwest side of the ridge. I have reinterpreted the western sequence as Jurassic Cucurpe Formation on the southwest overlain by Glance Conglomerate on an unconformity. The Glance underlies a normal sequence of Mortita, Mural and Cintura Formations on the northeast side of Cerro El Puerto. Gonzalez-Leon and others (2000) report that the conglomerate contains Albian clasts, suggesting that it may represent the base of the Late Cenomanian syntectonic Picacho Conglomerate. However, it still lies unconformably over the shale and sandstone of the southwest face of Cerro El Puerto. Accepted Cucurpe Formation lies 25km SW of Arispe and the shale lithologies at both localities appear very similar. An age date from fossils or a provenance study (presently in progress) should help resolve this question.

SONORA-SINALOA BATHOLITH

Batholithic scale magmatic activity is a common driving force in the development of porphyry style mineralization and the mobilization of boron that results in the formation of hydrothermal tourmaline during the final stages of magmatic crystallization of the batholithic mass. For these reasons a better understand the distribution of the batholithic masses of the region might prove useful.

After development of the Laramide (Late Cretaceous Early Tertiary), volcano-intrusive magmatic complex erosion locally exposed the batholithic phases. The extensive outpouring of the Sierra Madre Occidental Volcanic Province, during the Oligocene and Early Miocene, buried most of this erosion surface. Late Miocene extension during the opening of the Gulf of California broke the Tertiary cover, and subsequent erosion developed much of the presently observed batholith outcrop distribution. This highly fragmented distribution complicates plotting the distribution of the batholithic masses. Regional compilation maps such as Ortega-Gutierrez and others (1992) along with local mapping and associated age dating (McDowell, 2001) have improved our knowledge of the extent of Sonora-Sinaloa batholith. Limited modifications of the distribution of batholitic rocks have resulted from the regional mapping of this study. The tighter control of batholith distribution produced by these field observations have aided in the integration of field data with the aeromagnetic data of Mexico (SGM, 2001).

Regional variation of magnetic fabric and intensity allows connecting fragmented outcrop localities and the projection of the batholiths into regions lacking outcrop. The magnetic data and age dating (McDowell, 2001) indicate that distinct bodies of the batholithic complex exist with differing ages. The younger batholithic masses to the east (McDowell, 2001) are those that mostly intruded into proposed marginal basin sediments. The distribution of the combined Sonora-Sinaloa Batholithic complex (Fig. B.2), aids in the assessment of the possible association with B, Mo and Au mineralization.

GEOCHEMICAL DISTRIBUTION

Tourmaline, gold, molybdenum, nickel and cobalt distribution indicate a spatial correlation of these elements with the distribution of the deep marine Jurassic sediments. The proposed extent of the Sonora-Sinaloa Batholith suggests that the intersection of the batholith with the sediments is the most productive area for these types of mineralization. The mapped distribution results in part from the degree of Tertiary volcanic cover along the eastern margin of the area of interest.

Tourmaline.

Tourmaline distribution is based mostly on field observations (Fig. B.3) and published descriptions (Table B.1). The Western Mexican tourmaline province actually extends into southwestern Arizona with the Sierrita-Esperanza Mo-Cu district and runs at least as far south as central Sinaloa (Fig. B.3). Significant accumulations of tourmaline occur throughout this region mostly in the form of breccia pipes and quartz-sericite veins. In the Sierrita-Esperanza porphyry system tourmaline occurs as disseminations in the Jurassic Harris Ranch granodiorite and along the Mulatos River, north of Mulatos, it occurs in the form of a metamorphic halo around a felsic stock. Documented ages indicate an association with Laramide age batholiths and coeval volcanism with the possible lone exception of the Jurassic Harris Ranch intrusion.

Molybdenum and tourmaline occur together at Maria and La Colorada at Cananea, Sonora, and at Washington and Cumobabi, Sonora. Gold and tourmaline occur together at San Francisco, Sonora in quartz-sericite veins; southeast of Arivechi, Sonora and southwest of Matarachic, Sonora in breccia pipes, Sonora and in quartz-sericite veins in the Morelos region of Chihuahua.

Tourmaline occurrences appear to be underreported in general, so this compilation (Table B.1) derives principally from the field observations of this study. A literature search and inquiries of geologists with abundant experience in the region added some systems and further verified that few significant localities occur outside of the proposed Mezcalera Marginal Basin.

Some tourmaline localities external to of the Mezcalera Province occur within the region, such as Copper Creek west of the San Manuel, Arizona porphyry deposit. A strong tourmaline locality west of the Jurassic basin, north of Caborca is associated with a Laramide batholith which also cuts the Jurassic basin. Significant tourmaline occurs in Baja California but while it appears consistent with the general basin model, it occurs outside of the study area.

Molybdenum.

Most major Cordilleran molybdenum porphyry systems, associated with alkaline magmatism, occur well inboard of the related subduction but remain unknown in Mexico. A less important, but still significant, belt of Mo deposits occurs from Sierrita-Esperanza in Arizona through the Cumobabi District of central Sonora into southern Sonora. The majority of these Mo systems plot within the proposed limits of the Mezcalera Province (Fig. B.4). These deposits fall into the category of low fluorine Mo systems as proposed by Theodore and Menzie (1983).

Molybdenum grades in porphyry copper deposits of southwest North America may yield more detail from their greater abundance (compiled in Table B.2). Many problems exist with the numerical values reported. Reported Mo values, particularly as a byproduct, depend greatly on the relative economics of the metals at the time of evaluation and become problematic in attempting to compare metal distribution. Higher prices allow mining lower grades, thus bringing down the mined grade. Distribution of Cu and Mo in relation to each other within a deposit can also dramatically affect reported grades. The nature of the evaluated ore body bears directly on grade. At Cananea, the Maria pegmatitic lens and La Colorado pegmatitic-breccia pipe are very high grade but the more dispersed Mo shells in a porphyry system will yield lower grades but could have more contained metal.

If the Mo is only a byproduct the reported Mo grade in a porphyry copper deposit will not always be representative of the contained Mo of the system. If the Cu and inner Mo ore shells show significant separation, the Mo may be underrepresented by a lack of deeper drilling. Dos Pobres in eastern Arizona appears to have the reverse situation with higher Mo grades outside the Cu rich zone. Dos Pobres, Arizona Mo grades are estimated to be between 0.01 and 0.001 % Mo based on grade contouring (Langton and Williams, 1982). The published bulk Mo grade for Cananea is 0.02% Mo but specific phases of the system such as the Colorado Pipe contain significantly higher grades (0.80 % Mo). The Maria deposit of the Cananea District contains 0.36 % Mo, but it is in reality only a pegmatitic phase of the Marta stockwork deposit for which I have not found published results.

Despite these data problems, plotting the Mo grades from Table B.2 produces a strong spatial correlation with the proposed outline Mezcalera Basin (Fig. B.4). The change of Mo grades along the proposed Cananea Rift Fault is very dramatic, with the richer Mo deposits occurring along the margin and within the proposed Mezcalera Basin.

There are some known Mo-porphyry systems which are not economic or remain untested. Chirimoyo, Durango, displayed a broad suite of geologic features of a classic Colorado molybdenum deposit but did not contain enough Mo grade in the portion tested to be economic. Batopilas, Chihuahua, displays important potential as a Mo system but presently lacks testing directed at the Mo target.

Gold.

Most geologists involved in mineral exploration in Mexico recognize a gold belt paralleling Mexico's west coast as an important feature in Mexico's mineral distribution. Table 3 attempts to list most Mexican Au deposits with published production and reserves greater than 100,000 ounces of Au (Albinson and others, 2001). In addition to these estimates of gold content, information compiled includes tourmaline associations and geologic setting. In Figure B.5 the gold deposits are plotted with respect to the proposed Mezcalera Marginal Rift Basin and the Sonora-Sinaloa batholith. Approximately 2/3 of total ounces of those deposits with greater than 1 million ounces Au occur within the proposed limits of the Mezcalera Marginal Basin Province and it appears that most of those in the 100k to 1M ounce Au range are located within the province.

Nickel and Cobalt.

These metals are typically associated with mafic igneous systems. Perez and others (2005) documented five small low-grade nickel-cobalt systems in western Mexico (Fig. B.6). These occurrences are not economic but anomalous in their presence as epithermal systems. Extensive analytical results of mineralization at Batopilas reveal a small elevation of Ni and Co values in comparison with more typical hydrothermal systems.

DISCUSSION

The spatial distribution of Au, B, Mo, Ni and Co suggests a possible association between these elements and the Jurassic sediments of the proposed Mezcalera Province.

Boron and to a lesser degree molybdenum are known to be enriched in shale basins (Table B.4). Au, Ni and Co were initially thought to be related to the increased presence of oceanic crust to the west in the extended marginal rift basin, but there is also evidence that the sediments associated with submarine volcanism, as observed at Batopilas and Moris , may start out more enriched in these elements than the oceanic crust (Wedepohl, 1978). Because of the very low background levels of Au, there is generally a lack of data on gold distribution in crustal rocks. Gold on average is three times more abundant in basalt than granite (Table B.4) but even at 6 ppb Au remains near normal detection limits and may lack true significance.

Relation of tourmaline to shale basins.

Analysis of boron levels in a variety of rock types indicates that shale on average contains an order of magnitude greater amounts of B than other B-bearing rocks. Two possible paths for these elevated B levels include inclusion of B from subducted shale or the assimilation of shale from marginal basins by rising magmas. The spatial relationship of both the outcropping batholiths and tourmaline occurrences suggests that shale assimilation is probably the overriding control and the more dispersed tourmaline occurrences may relate to subducted shale. A gold-tourmaline association occurs at the San Francisco Gold Mine, in the Matarachic breccia pipes and in the Morelos district quartz-tourmaline veins.

Molybdenum.

Despite the difficulties of using mine assay data to accurately portray Mo levels in the various deposits, it appears that systematic differences do occur depending on the location of the porphyry mineral system in relation to the proposed Mezcalera Marginal Rift Basin Province. Boron and molybdenum-enriched magma systems spatially associated with Jurassic marine shale and submarine volcanism may reflect assimilation of B and Mo enriched shale by magma. This would suggest that the indicated basin is not superficial but of significant volume. The halo of intermediate Mo values around the proposed basin between 0.01 % and 0.015% Mo may reflect magmatic systems assimilating both continental and anomalous basin fill crust.

Gold.

Plotting of Au deposits in Mexico (Table B.3) in relation to the proposed Mezcalera Marginal Rift Basin Province suggests a possible relationship between the basin and Au mineralization (Fig.B.5). Approximately 2/3 of gold plotted lie within or along the basin margins. The proposed Mezcalera Province limits do include a large portion of the Mexican crust and forms a significant wall rock to Mexico’s Laramide and younger magmatism. Therefore the spatial correspondence between Au and the Mezcalera Basin may not be surprising. The abrupt drop in Au distribution across the east margin of the basin, the Cananea rift fault, northward into Arizona suggest that there may be more than just the coincidence of subduction associated magma and basin location.

The increased amounts of oceanic crust under an extended crust may play a role in increasing the gold content of magmas if they assimilate this oceanic crust as well. Detrital Au in a cratonic marginal basin is another possible Au source, but significant potential cratonic detrital Au sources are not known in the region.

Nickel and Cobalt.

Nickel-cobalt-rich systems along a rifted margin may represent greater oceanic crustal component, as the distance from the unextended craton increases. Ocean sediments deposited in submarine volcanic environment also appear significantly enriched in Ni and Co (Wedepohl, 1978).

CONCLUSIONS

Cretaceous through Holocene cover limits earlier Mesozoic outcrops and creates a major challenge in understanding of the Triassic and Jurassic history of western Mexico. The increasing number and focused distribution of probable Jurassic marine outcrops along Mexico's west coast encourages the integration of these outcrops into a unified basin from Arizona to at least as far south as Durango. Although a gap exists in the knowledge between Sinaloa and Durango, and southwest Mexico, south of the Trans-Mexican Volcanic Belt, the continuity of the Parral-Proaño overthrust, that thrusts sediments out of this basin, and the lithologic and age correlation between the north and south regions supports the presence of one continuous Mesozoic marginal basin along Mexico's west coast, the Mezcalera Marginal Rift Basin. More support for extending the basin at least as far south as Durango comes from the coincident distribution of tourmaline, Mo and Au within the proposed boundaries of the basin.

Magma evolution certainly affects metal distribution but newer more complete metal distribution maps produce different patterns than those proposed by Clark and others (1982). An improved understanding of the basement distribution in western Mexico highlights spatial correlations between B, Mo, Au, Ni and Co and the resulting proposed marginal rift basin. The proposed basin also parallels the plate boundary and the crustal composition is distinctly different from the adjacent crust. The spatial association of these elements with the Jurassic Mezcalera Marginal Rift basin probably has multiple causes, but the presence of submarine volcanism in the basin is potentially a major contributor to the metal character of mineral systems later formed within the basin limits.

Although still debated, evidence is strong that rising, subduction-associated magmas must derive much of their melt volume from assimilation of their hosting crust. If these magmas rise through a crust anomalous in a certain suite of elements, the resulting magmas should also become anomalous in these elements. Many other factors such as timing, volatile chemistry and content, structural controls and permeability will influence the final nature of magma driven mineral systems, but assimilated crustal chemistry appears to be potentially a significant component.

If the correlation between the proposed Mesozoic marginal rift basin, the Mezcalera Province, and the distribution of mineralization can be further documented, then it presents significant insight into the development of metallogenic provinces.

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FIGURES

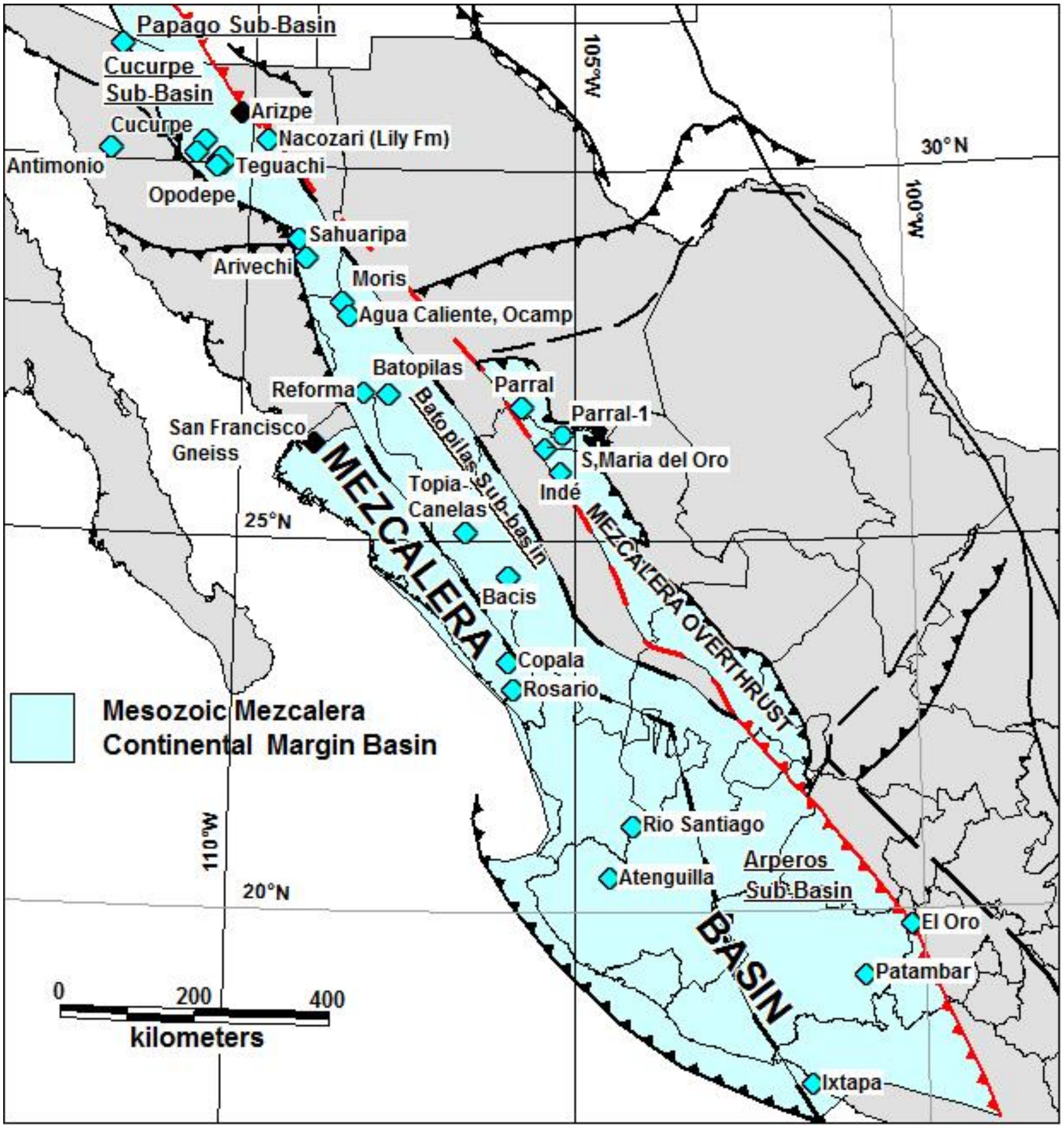

Figure B.1. Outcrops of the Mezcalera Basin sediments (blue diamonds) most of which have been visited as part of this study.

Fig. B.1 Near identical lithologies of turbiditic sand and mud observed at Parral, Sara Alicia and Chirimoyo suggest at least a similar slope depositional environment and possibly a similar age. Outcrops from Batopilas up through northern Sonora contain similar deep marine black shale, dated at Cucurpe and dated at Batopilas as Late Jurassic. The blue shaded area is the proposed area of the Mesozoic Mezcalera marginal rift basin and the Parral-Proaño thrust belt of these same sediments. Ixtapa and Atengilla are probably Late Cretaceous in age, while Parral sediments are dated by PEMEX as Late Jurassic and Early Cretaceous.

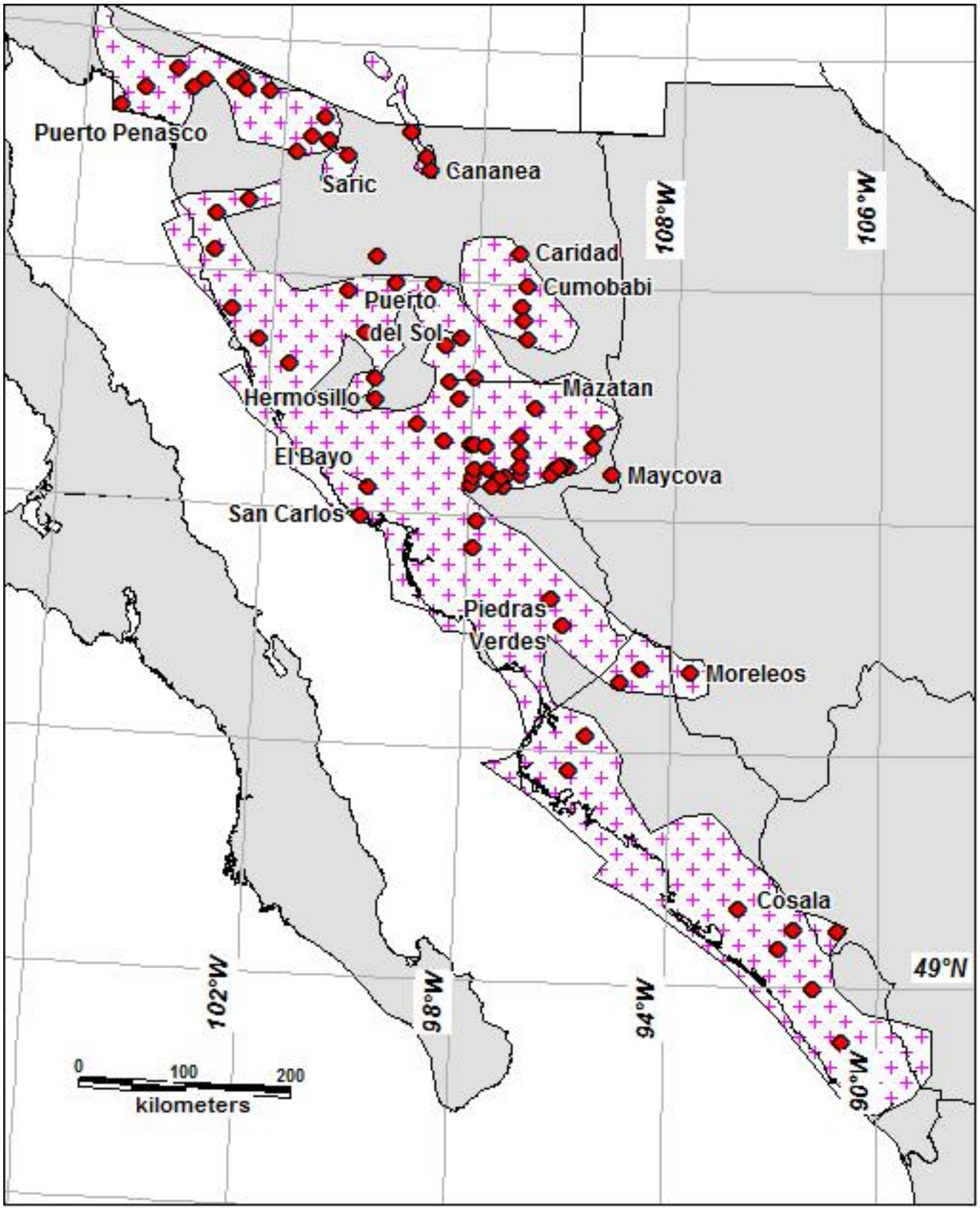

Figure B.2. Fabrics and intensities from the aeromagnetic map of Mexico along with field visits allow definition of Sonora-Sinaloa Batholith.

Fabrics and intensities from the aeromagnetic map of Mexico allow combining the many disconnected outcrops from the many maps of Mexico and regional studies into coherent masses that most likely represent the mostly buried distribution of the batholithic bodies (pink pattern). Red diamonds indicate outcrops visited during study.

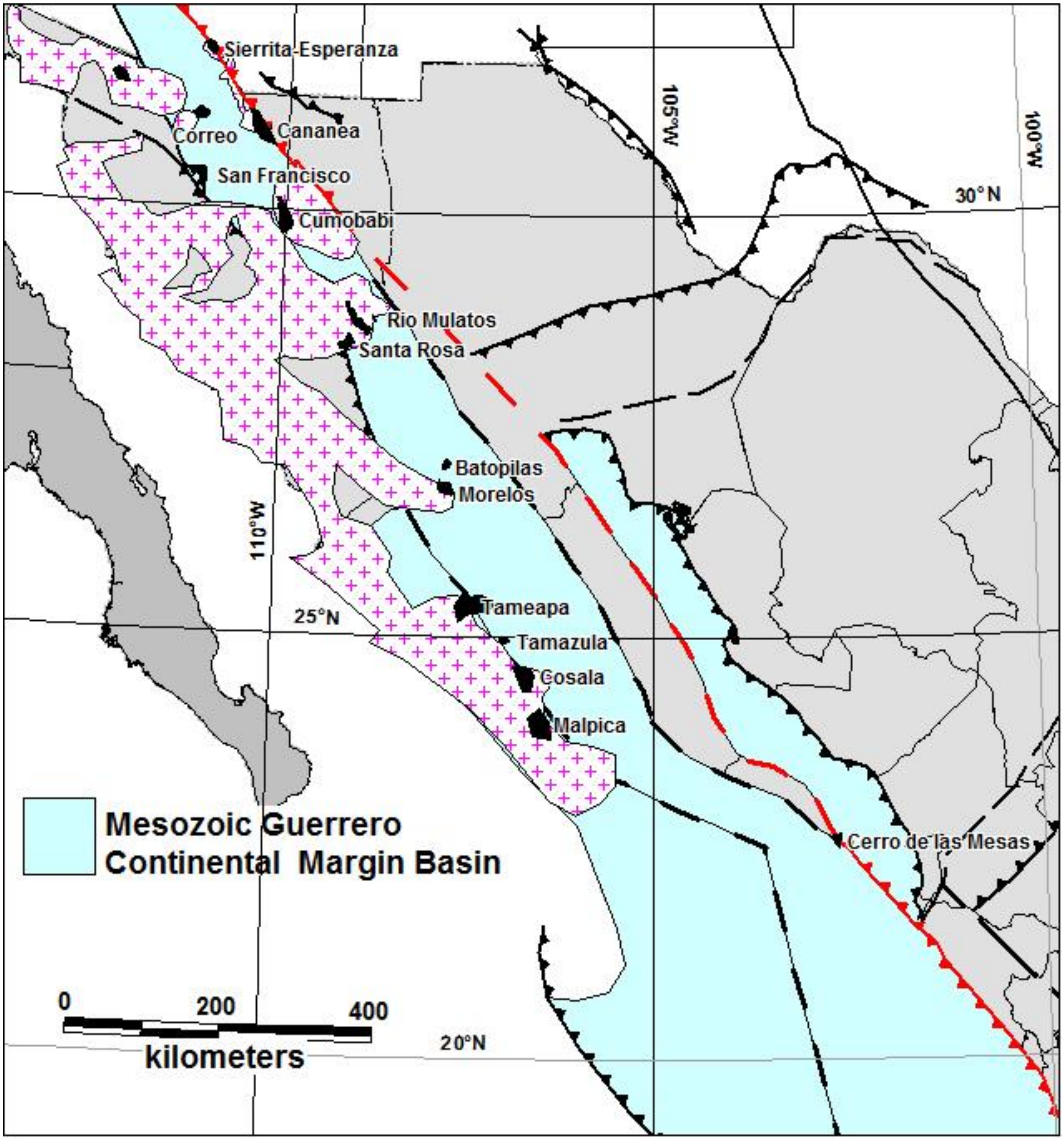

Figure B.3 Tourmaline occurrences (in black) in Mexico and SW Arizona show a spatial correlation with the intersection of the proposed Mezcalera Province (blue) and the Sonora-Sinaloa batholithic complex (pink pattern).

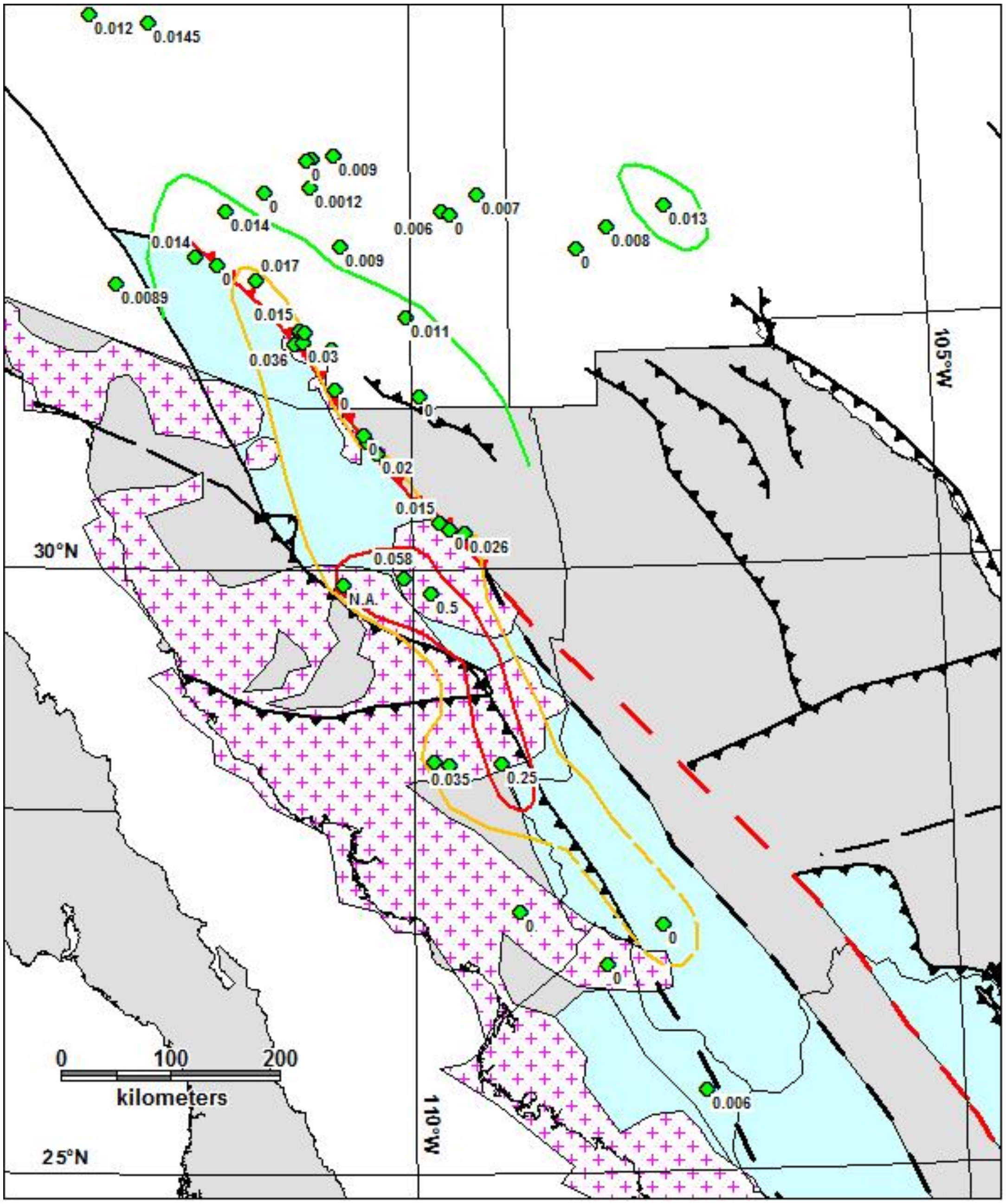

Figure B.4 Contour of the published Mo grades of Arizona, New Mexico and Northwest Mexico.

Figure illustrates the correlation between of the proposed Jurassic Mezcalera basin and Mo grades. This contoured data accentuates the proposed Cananea Rift Fault. Inside red contour is > than 0.02 % Mo, inside the orange contour is > than 0.015 % Mo and inside the green contour is > than 0.01 % Mo (other fields as Figure 2).

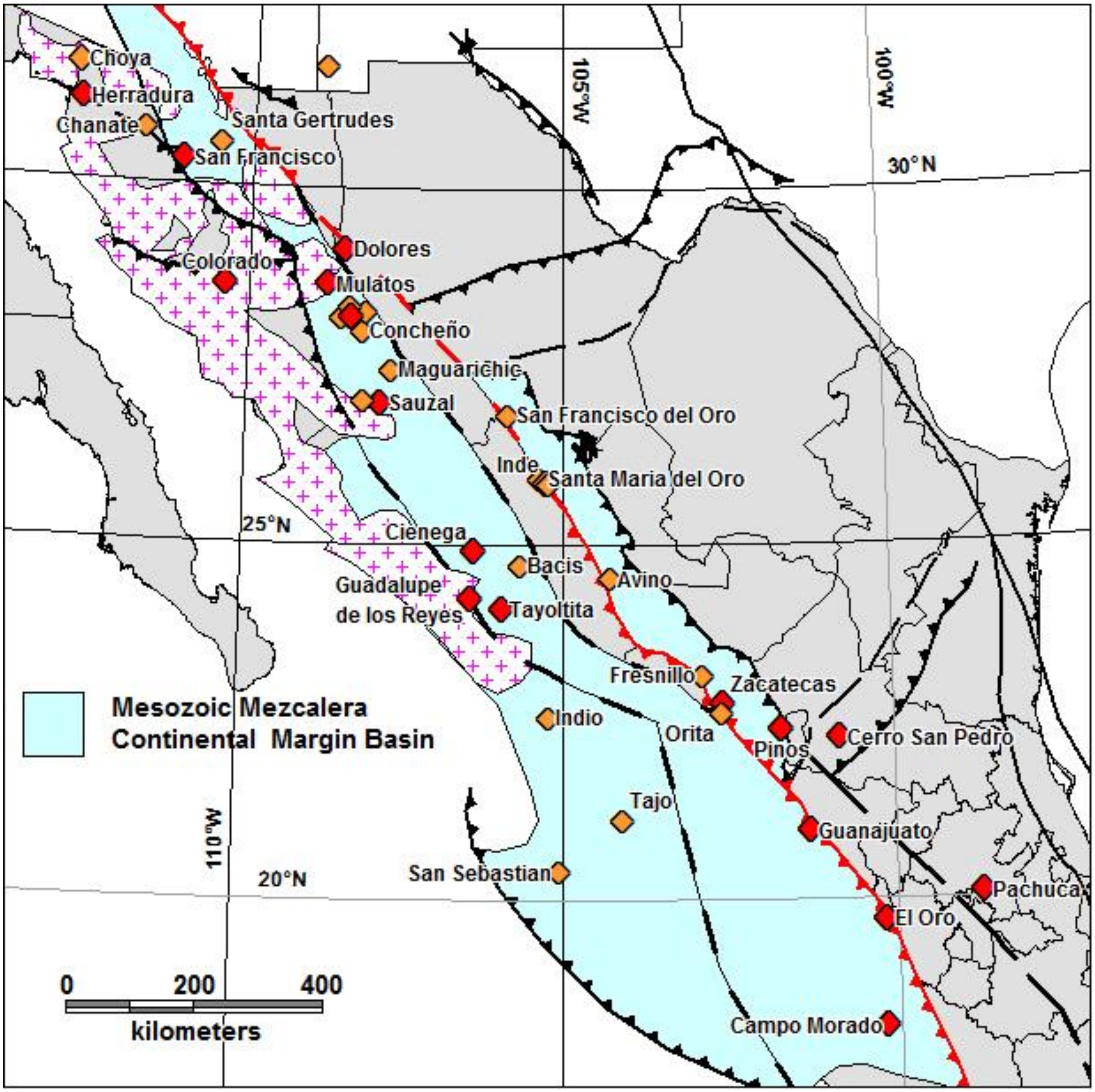

Figure B.5 A significant portion of Mexico's gold deposits show a strong spatial correlation with the proposed Jurassic marginal basin.

Red diamonds indicate deposits with ≥ 1 M ozs. Au production and reserves and orange diamonds denote between 1M ozs and 0.1 M ozs. (other fields as Figure 2).

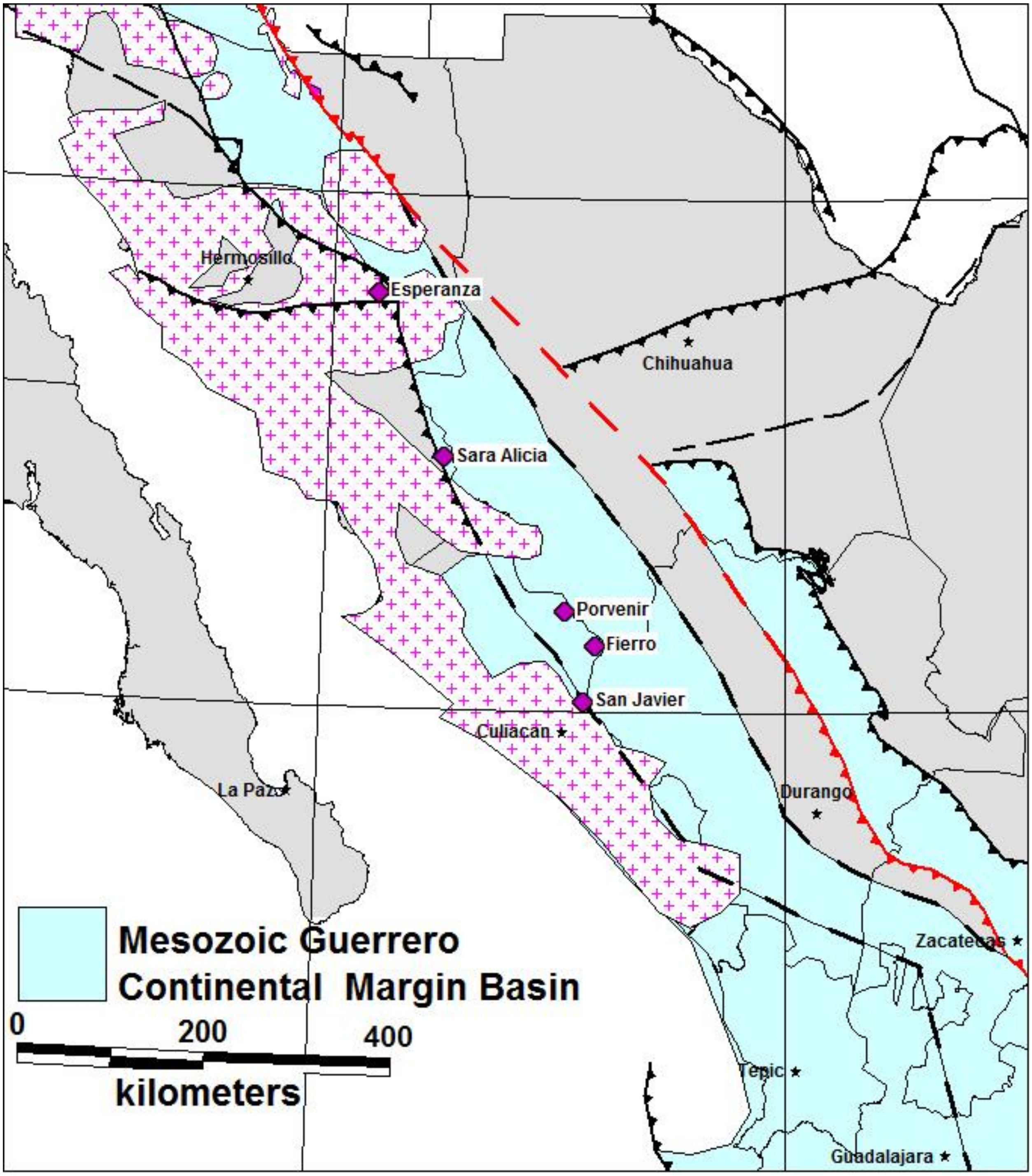

Figure B.6 The Ni and Co deposits (purple diamonds) of northwest Mexico (Perez-Segura and others, 2005), although sparse, show spatial correlation with the proposed Jurassic marginal basin (shaded blue).

Table B.1. Tourmaline occurrences in southwest North America

Name	Map Label	State	Location Latitude	Longitude	Nature of occurrence	Metals	Age	Field Visit	Reference
Copper Creek	CC	ARIZ			Mineralized Breccia pipes	Cu		*	Lyons, this study
Harris Ranch	HR	ARIZ			Disseminated			*	Lyons, this study
Sierrita-Esperanza	SE	ARIZ			Disseminated clusters	Mo, Cu		*	
Cananea	Ca	SON			Mineralized Breccia pipes	Cu, Mo		*	
Maria	Mr	SON			Pegmatitic Bx	Cu, Mo		*	
La Colorada Pipe	LC	SON			Pegmatitic Bx	Cu, Mo			
El Correo	EC	SON	31.125	-111.166	Bx, Q-Tourm vns, bull qtz vns				Smith +, 1987
San Francisco	SF	SON			Qtz tourm vns	Au		*	
Cumobabi	Cm	SON	29.800	-109.817	Breccia matrix	Mo, Cu		*	
Washington	W	SON			Breccia matrix	Cu, Mo		*	Lyons, this study
Sierra San Ignacio	SI	SON	28.720	-109.000	Breccia matrix	Cu, Au			
Rio Mulatos	RM	SON	28.744	-108.760	Contact halo	Cu		*	Lyons, this study
Santa Rosa	SR	SON	28.442	-109.116	Breccia matrix			*	Lyons, this study
Morelos	Mo	CHI			Qtz tourm vns	Au		*	Lyons, this study
Tameapa	Ta	SIN	25.633	-107.367	Stockwork and disseminated				
Malpica	Ml	SIN	23.250	-106.117	Bx filling and stockwork	Cu > Mo			
Cosala	Cs	SIN			Veins	Cu, Zn, Pb, Ag		*	

Table B.2. Southwest North America Porphyry Cu-Mo grades

DEPOSIT	STATE	Cu(%)	Mo(%)	Tonnage	Tourm	SOURCE
Cumobabi	Son	0.250	0.2600	11	Y	Barton et.al, 1995
Los Verdes	Son	0.200	0.2500	100		Long, 1995
Creston (Opedepe)	Son	0.150	0.1600			Perez, 1985
Washington	Son	1.710	0.0580	1	Y	Long, 1995
Sierrita-Esperanza	Ariz	0.330	0.0360	1168	Y	Long, 1995
Cuatro Hermanos	Son	0.431	0.0350			Barton et.al, 1995
Twin Buttes	Ariz	0.900	0.0300	129		Long, 1995
Caridad	Son	0.404	0.0260	1500		Long, 1995
Cananea	Son	0.700	0.0200	1850	Y	Barton et.al, 1995
Maria	Son	6.000	0.3600		Y	Wodzicki, 2001
La Colorada	Son	7.000	0.8000		Y	Wodzicki, 2001
Mission	Ariz	0.626	0.0190			Gilmour, 1982
Silver Bell	Ariz	0.770	0.0170			Gilmour, 1982
Florida-Barrigon	Son	0.300	0.0150			Barton et.al, 1995
Pima	Ariz	0.480	0.0150			Gilmour, 1982
Copper Basin	Ariz	0.400	0.0145			Singer et al, 2002, 2005
Sacaton	Ariz	0.720	0.0140			Singer et al, 2002, 2005
Vekol Hills	Ariz	0.560	0.0140			Long, 1995
Hillsboro (Copper Flat)	NM	0.450	0.0130			Singer et al, 2002, 2005
Bagdad	Ariz	0.530	0.0120			Long, 1995
Johnson Camp	Ariz	0.489	0.0110			Singer et al, 2002, 2005
San Manuel-Kalamazoo	Ariz	0.680	0.0090	503		Long, 1995
Inspiriation	Ariz	1.123	0.0090			Gilmour, 1982
Pinto Valley	Ariz	0.440	0.0090	258		Long, 1995
Morenci	Ariz	0.850	0.0090	957		Long, 1995
Santa Rita-Chino	NM	0.468	0.0080	439		Singer et al, 2002, 2005
Copper Cities	Ariz	0.530	0.0070	70		Long, 1995
Tameapa	Sin	0.400	0.0060		Y	Barton etal, 1995
Dos Pobres	Ariz	0.730	0.0060			Singer et al, 2002, 2005
Castle Dome	Ariz	0.330	0.0055			Singer et al, 2002, 2005
Helvetia	Ariz	0.552	0.0055			Singer et al, 2002, 2005
Ajo	Ariz	0.800	0.0050	388		Long, 1995
Ray	Ariz	0.950	0.0012	313		Long, 1995

Table B.3. Significant Au deposits of Mexico

Deposit	State	Mt Au	Tectonic Setting	Geologic setting	References †
Avino	Durango	0.203	Mezcalera Basin	Ter. Rhy vent	Albinson +, 2001
Bacis	Durango	0.422	Mezcalera Basin	Ter.rhy vent	Albinson +, 2001
Campo Morado	Guerrero	1.500	Mezcalera Basin	Volcanogenic massive sulf	Oliver +, 2001
Cerro San Pedro	San Luis Potosi	4.000			Peterson +, 2001
Chanate	Sonora		Papago		
Choya	Sonora		Papago		
Cienega	Durango	1.000	Mezcalera Basin	Ter Rhy flow dome	Albinson +, 2001
Colorado	Sonora	5.750	Caborca		Albinson +, 2001
Concheno	Chihuahua	0.438	Parral-Proano		Albinson +, 2001
Dolores	Chihuahua	2.450	Mezcalera Basin		Over
Fresnillo	Zacatecas	0.108	Mezcalera Basin		Albinson +, 2001
Guadalupe de los Reyes	Sinaloa	1.300	Mezcalera Basin	Dacite dome	Albinson +, 2001
Guanajuato	Guanajuato	5.000	Mezcalera Basin		Albinson +, 2001
Herradura	Sonora	2.000	Papago		
Inde	Durango		Parral-Proano		
Indio	Sinaloa	0.156	Mezcalera Basin		Albinson +, 2001
Maguarichic	Chihuahua	0.206	Mezcalera Basin		Albinson +, 2001
Moris	Chihuahua		Mezcalera Basin	Ter. intr.cutting Jur. Sed	
Mulatos	Sonora	2.500	Mezcalera Basin	Olig. Rhydac.dome	
Ocampo	Chihuahua	2.800	Mezcalera Basin	Olig. Rhydac.dome	Gammon Lake web site
Orito	Zacatecas	0.625	Parral-Proano		Albinson +, 2001
Oro	Mexico State	9.500	Mezcalera Basin		Albinson +, 2001
Pachuca	Pachuca	6.250			Albinson +, 2001
Pinos	Zacatecas	5.625	Parral-Proano		Albinson +, 2001
Rosario	Sinaloa	0.117	Mezcalera Basin		Albinson +, 2001
San Francisco	Sonora	1.000	Mezcalera Basin		
San Francisco del Oro	Chihuahua	0.312	Parral-Proano		Albinson +, 2001
San Sebastian	Jalisco		Mezcalera Basin		
Santa Gertrudes	Sonora		Mezcalera Basin		Alba, 1998
Santa Maria del Oro	Durango		Parral-Proano		
Sombrerete	Zacatecas	0.330	Parral-Proano		Albinson +, 2001
Suazal	Chihuahua	2.000	Mezcalera Basin		
Taxco	Guerrero	0.280	Mezcalera Basin		Albinson +, 2001
Tayoltita (San Dimas)	Durango	9.750	Mezcalera Basin		Clarke +, 1988
Zacatecas	Zacatecas	2.110	Parral-Proano		Albinson +,2001

† All references dated 2001 are from Albinson and Nelson, 2001

Table B.4. Average element background levels of B, Mo, Ni, Co and Au for various crustal rocks in ppm

Element	Crust	Basalt	Granite	Shale	Ocean Ridge Sediments	Sandstone	Carbonate	SEA H_2O
B	10	5	15	130	N.A.	35	20	4.6
Mo	1	1.5	2.0	2-2.6	N.A.	0.2	0.4	0.01
Ni	75	150	0.5	68-95	160-320	2	20	0.002
Co	25	48	1	19-20	80-160	0.3	0.1	0.0001
Au	0.004	0.006	0.002	N.A.	N.A.	N.A.	N.A.	.00004

Taylor, 1964; Turekian and Wedepohl, 1961; Wedepohl 1978

APPENDIX C GLOSSARY

.**Geosyncline**- terminology used to describe long linear synclinal basins believed to be down warps of the crust in which sediment collected. An aspect of the geosynclinal theory that ruled geology before the development of plate tectonics. In pre-plate tectonics literature the term was used to refer to the Mexican Basin.

Rise deposits- The rise deposits are comprised mostly of turbiditic deposits derived from slope, shelf and deltaic discharges interbedded with pelagic strata (Emery, 1977).

Shelf deposits- The shelf or neritic phase are usually thin bedded shale and carbonate sediments rich in carbonate when marginal to carbonate banks and reef complexes. Observed in the Lower Cretaceous strata of the Mezcalera Basin south of

Slope deposits- The slope strata are the overbank deposits from the turbidite channels feeding the rise deposits below (Emory, 1977). They are usually fine grained laminated except for the disperse turbidite channel deposits that can be coarser grained.

Storm rip-up clast- product of wave troughs reaching below the normal wave base and ripping-up laminar mud layers, carbonate or siliciclastic, and redepositing them as randomly stacked platy fragments. Occur as sheets on shallow below wave base carbonate banks or sediment shelfs and potentially produce greatly increased permeability along these horizons.

Trough- a term for long linear basins in geosynclinal theory. Also used as a geomorphic term. Conveys a sense of length and depth but no tectonic information inferred.

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Vita

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